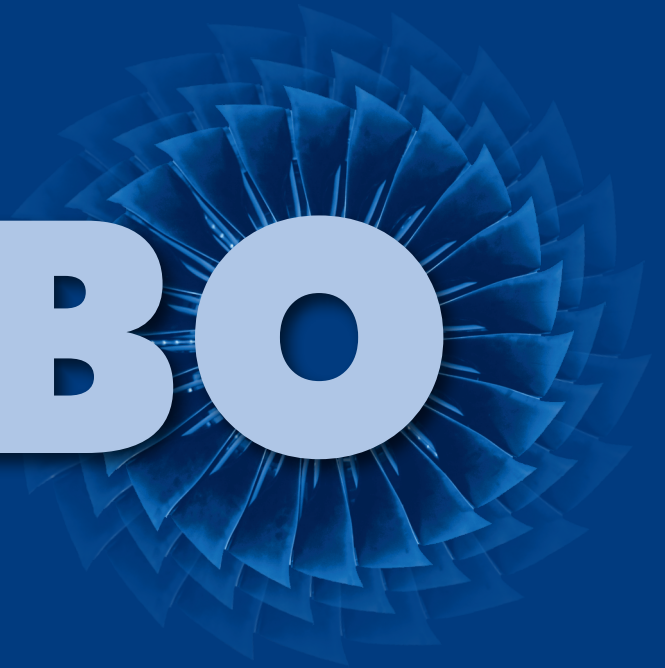




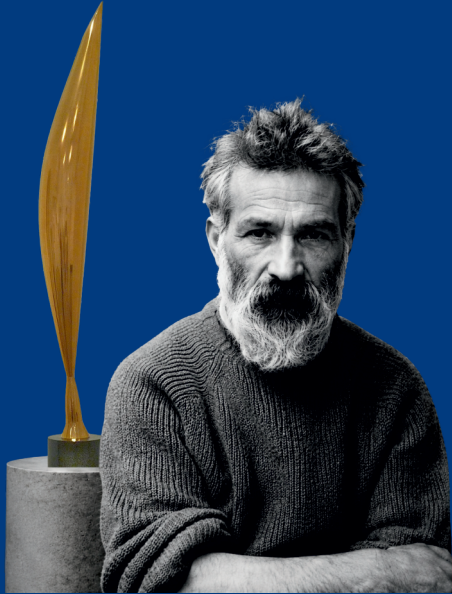
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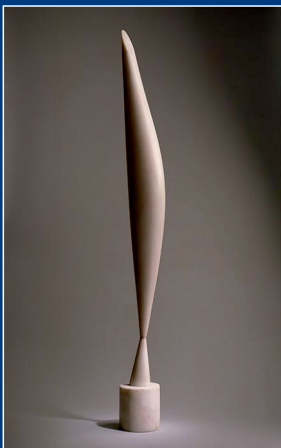
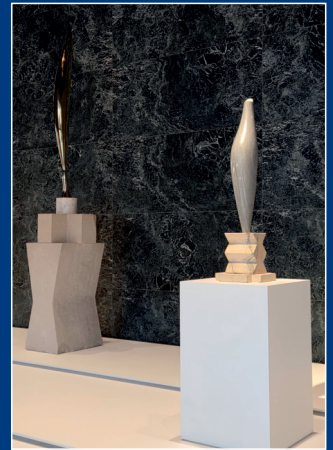


Brâncuși 150 Years of Vision

From “*Bird in Space*” to the Propulsion Technologies of the Future

There are creations that transcend both time and discipline. “Bird in Space”, the masterpiece of Constantin Brâncuși, does not depict a bird in the conventional sense; rather, it captures the essence of flight, the aspiration toward elevation, and humanity’s enduring desire to surpass known boundaries. Through the purity of its forms and the elegance of its lines, the sculpture becomes a powerful expression of movement and progress.

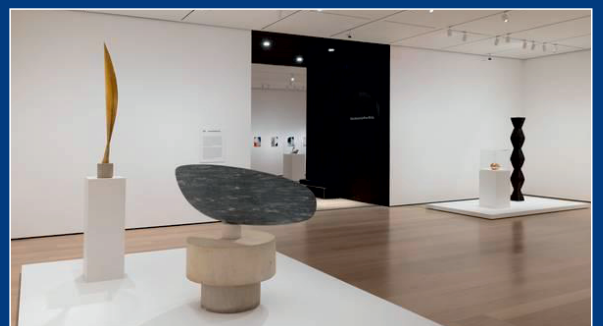
Nearly a century later, that same aspiration can be found in another field of Romanian excellence: scientific research and technological development. COMOTI - Romanian Research & Development Institute for Gas Turbines transforms the idea of flight from an artistic symbol into an engineering reality through advanced projects and technologies dedicated to aeronautics, energy systems, and propulsion.



If Brâncuși sought the essence of flight through art, COMOTI’s researchers and engineers explore its mechanisms and expand its possibilities through science. In both cases, excellence is rooted in the same philosophy: the pursuit of efficiency, the reduction of unnecessary complexity, and the courage to imagine what does not yet exist.

Viewed together, “Bird in Space” and COMOTI’s activity illustrate the continuity of a distinctly Romanian vocation for innovation and excellence. One poetically expresses the dream of overcoming gravity; the other provides the technological means to turn that dream into reality. Between Brâncuși’s polished bronze and COMOTI’s research laboratories lies a symbolic bridge — one built by the creative spirit that transforms bold ideas into enduring achievements.

Thus, if “Bird in Space” may be seen as a metaphor for freedom and ascension, COMOTI’s work represents the contemporary expression of that same ambition to continually push the frontiers of knowledge and technology. Ultimately, art and science share a common mission: to give shape to dreams and to open new horizons for future generations.



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Nimic nu se potrivește cu o idee neclară

Rățiunea umană pare să înceapă exact în aceasta stare: o lume fără granițe clare, în care experiența precede definiția. Primii oameni nu au moștenit categorii pentru „materie”, „forță” sau „cauză”; realitatea era în mare parte inefabilă — o simțeau și acționau asupra ei, dar încă nu o articulaseră. De-a lungul mileniilor, limbajul a contribuit la conturarea unei structuri din această ambiguitate, cultura a stabilizat-o, iar știința a rafinat-o în modele din ce în ce mai precise. Am trecut de la simțire la metafore, și în cele din urmă, la sisteme de legi și formalizme.

Viziunea lui Thomas Kuhn asupra revoluțiilor științifice surprinde perfect acest ritm: cunoașterea nu se acumulează liniar, ci se reorganizează prin schimbări succesive de paradigmă, fiecare redefinind însăși noțiunea de explicație. Ceea ce odată era inefabil devine formalizat, doar pentru a fi ulterior reîncadrat. Derek Muller a remarcat că, din moment ce fiecare generație găsește ceva de îmbunătățit la corpul de cunoștințe existent, toată știința este într-o oarecare măsură greșită. Progresul nu înseamnă doar evoluția modelelor și a teoriilor, ci evoluția înseși a cadrelor de referință în care le folosim.

În mod paradoxal, unele dintre cele mai puțin „pure” domenii — termodinamica, mecanica fluidelor, în general ingineria — se numără printre cele mai influente în viața de zi cu zi. Din necesitatea satisfacerii scopurilor practice, abandonăm definiția înțelegerii ca „înțelepciune” în favoarea definiției sale secundare: „acceptare” ^[1]. Aceste domenii sunt utile nu pentru că fundamentele lor sunt impecabile, ci pentru că le înțelegem limitele.

Tocmai această modestie științifică, obținută cu greu, a declanșat schimbarea filosofică din secolul al XX-lea — o distanțare de viziunea deterministă conform căreia oamenii de știință ar putea descoperi legile absolute ale Naturii, îndreptându-ne spre termeni mai modești precum „o teorie a” sau „un model al” realității.

Totuși, există ceva în spiritul uman care ne împinge înainte, rezistând tentației de a ne mulțumi exclusiv cu utilitatea. Ne întoarcem în mod repetat la problema adevăratului sens, chiar și atunci când am obținut deja un succes în a prezice comportamentul naturii. Căutarea înțelegerii persista ca un scop în sine, nu un simplu instrument. Și astfel, datorită sistemului nostru de valori, tehnologia și, de fapt, întreaga știință, îi este subordonată culturii (chiar dacă poate îi este necesară în mod fundamental).

O frontieră a erei noastre este încercarea de a defini inteligența, creativitatea și conștiința în termeni operaționali. Succesul inteligenței artificiale generative oferă răspunsuri parțiale, dar nu ne satisface dorința pentru o explicație mai profundă. Încă ne întrebăm nu doar ce funcționează, ci și ce înseamnă.

Dacă până și cele mai abstracte domenii științifice au încă nevoie de axiome după milenii de progres, poate că surprinderea completă a inefabilului va rămâne mereu imposibilă. Cu toate acestea, înțelegerea limitelor a ceea ce poate fi cunoscut nu este o retragere din fața căutării înțelepciunii, ci una dintre cele mai înalte forme ale sale.

Dr. Valeriu DRAGAN

¹ Arnold Sommerfeld remarcă: "Termodinamica este un domeniu amuzant. Prima dată când o parcurgi, nu o înțelegi deloc. A doua oară crezi că o înțelegi, cu excepția unor probleme punctuale. A treia oară știi că nu o înțelegi, dar ești deja atât de obișnuit cu sentimentul încât nu te mai deranjează."

Nothing fits an unclear idea

Human cognition appears to begin in precisely that state: a world without crisp boundaries, where experience precedes definition. Early humans did not inherit categories for “matter,” “force,” or “cause”; reality was largely ineffable—felt and acted upon, but not yet articulated. Over millennia, language helped carve structure out of this ambiguity, culture stabilized it, and science refined it into increasingly precise models. We moved from feeling, to metaphors, and finally to formal systems of law.

Thomas Kuhn’s account of scientific revolutions captures this rhythm perfectly: knowledge does not accumulate linearly but reorganizes through successive paradigm shifts, each redefining what counts as an explanation itself. What once was ineffable becomes formalized, only to be reframed again. Derek Muller remarked that since each generation finds something to improve on the existing body of knowledge all science is somewhat wrong. Progress, is not just the evolution of models and theories, but the evolution of the very frameworks in which we use them.

Paradoxically, some of the least “pure” domains—thermodynamics, fluid mechanics, engineering—are among the most powerful in shaping everyday life. For the sake of practicality, one abandons the definition of understanding as “wisdom” in favor of its secondary definition: “acceptance”². These fields are useful not because their foundations are flawless, but because we understand their limits.

It is this hard-won scientific humility that prompted the philosophical shift in the 20th century—moving away from the bold, deterministic view that scientists can discover the absolute laws of Nature, toward more modest terms like a “theory of” or “model of” reality.

Still, there is something in the human spirit that drives us forward, resisting the urge to settle for utility alone. We repeatedly return to the question of true meaning, even when predictive success is already achieved. The pursuit of understanding remains an end in itself, not merely a tool. And so it is because of our system of values that technology and in fact all science is subordinate (perhaps also foundational) to Culture.

A frontier of our current era is the attempt to define intelligence and creativity in operational terms. The success of generative AI provides partial answers, yet it does not satisfy our desire for deeper explanation. We still ask not only what works, but what it *means*.

If even the most abstract sciences still require foundational axioms after millennia of progress, perhaps fully capturing the ineffable will always remain impossible. Yet, understanding the limits of what is knowable is not a retreat from wisdom, but one of its highest forms.

Dr. Valeriu DRAGAN

² As Arnold Sommerfeld famously remarked: “Thermodynamics is a funny subject. The first time you go through it, you don’t understand it at all, the second time you think you understand it, except for one or two points, and the third time you know you don’t understand it, but by then you are so used to it that it doesn’t bother you anymore.”

DESIGN AND OPTIMIZATION OF THE WING AND CONTROL SURFACES FOR A FIXED-WING UAV

Flavia-Elena BLAGA¹, Mădălin DOMBROVSKI^{1*}, Tiberius FRIGIOESCU, Petre-Gabriel BADEA¹, Maria CĂLDĂRAR¹, Răzvan ROMAN²

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Corresponding author:

madalin.dombrowschi@comoti.ro

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ABSTRACT: This paper presents the aerodynamic and geometric design of the main lifting surface and lateral control system for a fixed-wing hybrid VTOL unmanned aerial vehicle, with a specific focus on optimizing performance within the low Reynolds number regime. The primary objective of the study is to determine the optimal airfoil selection, structural layout, and control surface sizing to ensure maximum mission endurance, structural integrity, and effective roll authority throughout the cruise flight envelope. The research employs comparative aerodynamic analysis, statistical sizing methodologies, and analytical verification principles to define a wing configuration that effectively balances high-lift requirements with the necessity for low-drag cruise efficiency. The design process encompasses the evaluation of reflex airfoils to enhance longitudinal stability, the development of a hybrid structural architecture to mitigate aeroelastic phenomena, and the integration of differential ailerons to fulfill lateral maneuverability requirements while minimizing adverse yaw. The findings indicate that the proposed wing geometry offers meaningful improvements in aerodynamic efficiency and stability margins compared to standard solutions, while the analytical validation confirms that the lateral control system provides sufficient authority to meet tactical agility demands. The study concludes that the proposed aero-structural design provides a balanced and robust solution for extended-range UAV applications, establishing a solid foundation for further flight dynamics optimization.

KEYWORDS: UAV, VTOL, AILERON, FIXED WING

¹ Romanian Research and Development Institute for Gas Turbines COMOTI

* Correspondence author: madalin.dombrowschi@comoti.ro

² Independent Researcher

NOMENCLATURE**Capital Letters**

AR	Aspect Ratio
C_a	Planform chord
C_D	Drag coefficient
C_{D0}	Parasitic drag coefficient
CFD	Computational Fluid Dynamics
CFRP	Carbon Fiber Reinforced Polymers
C_L	Lift coefficient
C_{Lmax}	Maximum lift coefficient
C_m	Pitching moment
D_i	Induced drag
FW-VTOL	Fixed Wing - Vertical Take-Off and Landing
L/D	Lift-to-Drag ratio
OML	Outer Mold Line
P	Roll angle
S	Wing area
S_a	Planform area
UAV	Unmanned Aerial Vehicle
V_{stall}	Stall air speed
VTOL	Vertical Take-Off and Landing

Lowercase Letters

b	Wing span
b_a	Planform span
b_{ai}	Spanwise location of the inboard edge
c	Chord
e	Oswald efficiency factor
k	Drag constant
m	Mass

Greek Symbols

α	Angle of attack
δ_{Amax}	Maximum upward and downward deflection angles
ρ	Air density
τ	Aileron effectiveness

Subscripts and Superscripts

0	Parasitic / Zero-lift baseline
a	Aileron / Planform
ai	Aileron inboard
Amax	Maximum aileron deflection
D	Drag
i	Induced
L	Lift
m	Pitching moment
max	Maximum
stall	Stall condition

1. INTRODUCTION

The aerodynamic performance of fixed-wing Unmanned Aerial Vehicles (UAVs), particularly those operating in hybrid VTOL configurations, relies fundamentally on the optimization of the main lifting surface. Current research emphasizes that the wing design is the critical element in resolving the contrast between the high-lift requirements of the hover phase and the low-drag necessity of the cruise phase [1, 2]. In the regime of low Reynolds

numbers ($Re \approx 10^5$) characteristic of the operational envelope for medium-class UAV wings, standard aerodynamic theory predicts a significant decline in efficiency due to laminar separation bubbles. To counteract this, the selection of the airfoil becomes paramount. Specialized airfoil series are extensively documented in recent literature as benchmarks for wing profiles, offering a critical balance of high lift-to-drag ratios and low pitching moments (C_m), which is essential for minimizing trim drag and enhancing the overall aerodynamic efficiency of the platform [3, 4, 5].

From a structural perspective, maintaining the precise aerodynamic shape of the wing under variable loading conditions has rendered traditional monolithic material approaches less effective. While carbon fiber reinforced polymers (CFRP) provide excellent skin stiffness, the selection of sustainable and damping-capable materials is becoming a priority in modern design [6]. Consequently, a growing body of research advocates for hybrid wing architectures and advanced composite integrations. Recent reviews of VTOL technologies [7] and composite manufacturing techniques [8] highlight the advantages of multi-material structures. When optimized internal ribs are combined with aerospace-grade spars and encased in a composite skin, the resulting assembly exhibits superior structural integrity and fatigue resistance compared to traditional designs [9, 10]. This advanced structural approach is particularly relevant for the wing assembly, which must dissipate concentrated loads without inducing critical stress concentrations, a subject extensively analyzed in recent numerical optimization frameworks [11, 12].

Essential to the wing's overall performance is the design and placement of its primary control surface: the aileron. The lateral authority of high-aspect-ratio wings remains a focal point of aerodynamic optimization. The use of outboard ailerons is the prevailing standard for roll control, yet their implementation in the wing trailing edge faces strict limitations. Literature suggests that for UAV wings, the effectiveness of control surfaces can be compromised by bio-inspired constraints or complex flow separation phenomena [13, 14]. To mitigate these effects, classic and modern wing design methodologies emphasize the importance of interference handling and precise geometric sizing to prevent pressure leakage and optimize control authority [15, 16].

Furthermore, the structural integration of these control surfaces into hybrid wings poses unique challenges regarding aeroelasticity. The actuation mechanisms housed within the wing must be rigid enough to prevent control reversal (aeroelastic twisting of the wing box) while remaining lightweight [17, 18]. Recent computational fluid dynamics (CFD) and flight dynamics principles confirm that optimizing the aileron parameters is critical for ensuring linear roll response without stalling the wing tip during low-speed maneuvers [19, 20]. By synthesizing these advanced aerodynamic profiles with hybrid structural solutions, current engineering practices aim to maximize endurance and payload capacity. This continuous improvement is supported by extensive theoretical and experimental studies on low Reynolds number flows [21, 22] and advanced flight control dynamics [23, 24], pushing the boundaries of what is achievable in non-military and tactical UAV applications [25].

2. AIRFOIL ANALYSIS AND SELECTION

The aerodynamic efficiency of the lifting surface is the primary determinant of performance for any UAV targeting long-endurance missions. For this specific hybrid VTOL platform, the operational flight envelope is characterized by a medium Reynolds number regime ($Re \approx 5.3 \times 10^5$), a condition where boundary layer management becomes critical. As noted in [1, 26], operating in this regime poses significant challenges, as traditional turbulent flow airfoils often suffer from the formation of laminar separation bubbles, leading to a drastic increase in drag. Based on the structural constraints detailed in the technical design and extensive computational analysis, the MH 114 airfoil was selected as the optimal solution.

2.1. Characteristics of the MH 114 Airfoil

The MH 114 is a "reflex" (auto-stable) airfoil. While originally conceived for tailless flying wing configurations, it has proven highly effective for conventional and V-tail UAV architectures due to its inherent longitudinal stability [4], a critical factor in flight dynamics analyzed by Stengel [27].

Selection argument:

a. Low pitching Moment (C_m): Unlike classic cambered airfoils described in standard wing theory [28, 29], the MH 114 features a reflexed mean camber line near the trailing edge, resulting in a near-zero or slightly positive pitching moment ($C_m \approx +0.02$). This characteristic significantly reduces the trim drag penalty. As indicated in aircraft design methodologies [15], a lower C_m requires less downward force from the empennage to balance the aircraft, thereby improving the overall Lift-to-Drag (L/D) ratio of the entire airframe. This reduction in interference and trim drag is consistent with the optimization principles outlined in Hoerner's foundational work on fluid-dynamic

drag [30].

b. **Laminar Flow at Low Reynolds Numbers:** At $Re \approx 500,000$, standard thick airfoils are prone to early transition. The MH 114 is geometrically optimized to maintain laminar flow over 40-50% of the upper surface chord, delaying the transition to turbulent flow and minimizing skin friction drag, a behavior predicted by XFOIL analysis methods [31] and validated in low-Reynolds surveys [3, 32], contrasts with the high-lift but high-drag philosophies often seen in general aviation [33].

c. **Relative Thickness and Structural Integration:** With a thickness-to-chord ratio of approximately 13%, the MH 114 offers an ideal compromise between aerodynamics and structures. This volume is critical for accommodating the hybrid spar assembly (aluminum rectangular profile) and the birch wood ribs without altering the outer mold line (OML). This supports the hybrid material approach advocated by recent research [7], ensuring sufficient stiffness without the weight penalty of solid composite structures.

d. **Polars and Aerodynamic Fineness:** At the design cruise lift coefficient ($C_L \approx 0.5 - 0.6$), the MH 114 exhibits its maximum aerodynamic efficiency ("drag bucket"). This aligns perfectly with the energy conservation requirements of the hybrid propulsion system, extending the mission endurance as per the sizing methodologies found in standard design literature [14, 34].

2.2. Comparative Study: MH 114 vs. Established Baseline Airfoils

To validate the selection of the MH 114, a rigorous comparative analysis was conducted against widely recognized baseline profiles: the Clark Y and the NACA 2412.

2.2.1. MH 114 vs. Clark Y

Clark Y is a widely used airfoil in small-scale aviation due to its high maximum lift and flat bottom, which simplifies construction.

- **Clark Y disadvantages:** According to wind tunnel data from Althaus [35], it generates a significant negative pitching moment ($C_m \approx -0.08$). This would necessitate a larger, heavier tail structure or high trim angles to maintain equilibrium. Furthermore, its drag polar degrades faster at higher cruise speeds (70 km/h) compared to laminar profiles [36].
- **MH 114 advantages:** Offers superior longitudinal stability and reduced drag at the specific Reynolds number of the mission [12].

2.2.2. MH 114 vs. NACA 2412

NACA 2412 is a classic general aviation airfoil known for its forgiving stall characteristics.

- **NACA 2412 disadvantages:** The pressure recovery gradient on the NACA 2412 is steeper, leading to an earlier transition to turbulent flow. Jacobs and Sherman [37] demonstrated that at $Re \approx 5 \times 10^5$, such profiles incur higher friction drag compared to modern designs. Additionally, Mueller [38] notes that "older" NACA sections are less efficient in the regime where laminar separation bubbles are prevalent.
- **MH 114 advantages:** Maintains a wider range of C_L with low drag and induces lower torsional loads on the wingstructure, a vital factor for the durability of the hybrid wood-composite joints [18].

2.3. Conclusion of selection

To provide a transparent and objective baseline for the selection process, a clearer quantitative comparison of the primary aerodynamic metrics for the three evaluated airfoils at the operational cruise regime ($Re \approx 5.3 \times 10^5$) is summarized in Table 1.

Table 1 Quantitative Aerodynamic Comparison at $Re \approx 5.3 \times 10^5$

Airfoil	Max Lift-to-Drag Ratio (L/D)	Pitching Moment (C_m)	Max Lift Coefficient ($C_{L,max}$)	Thickness (t/c)
MH114	≈ 139	+0.02	1.40	13.0%
Clark Y	≈ 115	-0.08	1.55	11.7%
NACA 2412	≈ 122	-0.05	1.50	12.0%

The adoption of the MH114 represents an engineering optimization driven by the specific constraints of the

hybrid VTOL architecture. This choice ensures minimized trim drag, sufficient structural volume for the hybrid skeleton, and a validated capability to sustain cruise speeds with minimal power consumption, complying with the endurance goals of modern UAV platforms.

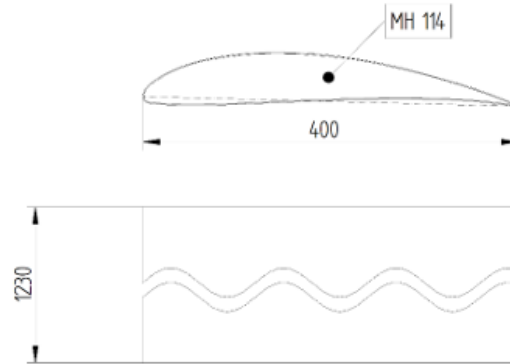


Figure 1 Wing dimensions

3. THEORETICAL RESEARCH ON THE AERODYNAMIC AND STABILITY ANALYSIS OF THE FIXED-WING UAV STRUCTURE WITH VTOL SYSTEM

3.1. Aerodynamic calculation of the unmanned aerial platform

The UAV analyzed in this study is a fixed-wing platform with VTOL capability. The wing geometry includes a wingspan of approximately 2.5 m, an average chord of 0.4 m, and a resulting lifting surface of about $S \approx 0.98 \text{ m}^2$. In the following, the main design values are justified with a total mass of 35 kg and a cruise speed of 70 km/h, by reference to fundamental aerodynamic principles and specialized literature.

Recent studies dedicated to the design of FW-VTOL and hybrid systems show that efficient platforms with high endurance and VTOL capability currently fall within the 20–30 kg MTOM range. He et al. presents a design methodology for a 30 kg electric FW-VTOL UAV, optimized for load distribution between VTOL propulsion and cruise propulsion [39]. Furthermore, research on hybrid architectures demonstrates that these systems become significantly more efficient within the medium-mass category ($\approx 15\text{--}35 \text{ kg}$), allowing for the exploitation of fuel energy without excessive weight disadvantages [40]. These results are confirmed by experimental evaluations of hybrid propulsion for UAVs, which show that the mass of the hybrid system (thermal engine + generator + batteries) can represent 35–45% of the MTOM, being typical for 20–30 kg platforms intended for extended-endurance missions [41]. In addition, consolidated commercial data for similar platforms confirm the same logic: the FW-VTOL UAV JOUAV CW-25, widely used in surveillance and mapping, has an MTOW of approximately 25 kg [42].

For a wingspan of 2.5 m and chord of 0.4 m, the wing payload becomes:

$$\frac{W}{S} \approx 250 - 300 \text{ N/m}^2 \quad (1)$$

a characteristic value for medium-class UAVs designed to operate in cruise flight at moderate speeds. The lift coefficient determined above corresponds to an angle of attack of approximately 6° , which lies within the usual flight range for aircraft of this type, where the optimal lift-to-drag ratio is generally achieved.

At sea-level air density, a cruise speed of 70 km/h (19.4 m/s) requires an approximate lift coefficient of:

$$C_L \approx 1 \quad (2)$$

This value is located exactly within the optimal range for airfoils intended for small and medium UAVs. Kapoulas et al. show, through a detailed analysis of airfoil selection optimized for UAVs, that maximum performance (high lift-to-drag ratio) typically occurs in the range $Re \approx (3 - 6) \times 10^5$, associated with cruise speeds of 18–25 m/s for wings with chord lengths of 0.3–0.5 m [43].

For the analyzed configuration, the Reynolds number at 70 km/h is:

$$Re \approx 5.3 \times 10^5 \quad (3)$$

The figures below illustrate the main aerodynamic characteristics of this airfoil, namely the airfoil polar, which describes the relationship between the lift coefficient C_L and the drag coefficient C_D ; the variation of aerodynamic efficiency, expressed by the ratio C_L/C_D , as a function of the angle of attack; as well as the variation of the lift and drag coefficients with the angle of attack. These characteristic curves were computed and validated for the speed corresponding to the aircraft's cruise regime, which was set to approximately 70 km/h. The presented plots (Figure 2, Figure 3, Figure 4, Figure 5) illustrate the theoretical aerodynamic coefficients calculated with XFLR5 analysis software. By setting the simulation parameters to match the aircraft's operational cruise regime, the software provided the essential lift-to-drag ratios and coefficient variations necessary for performance validation.

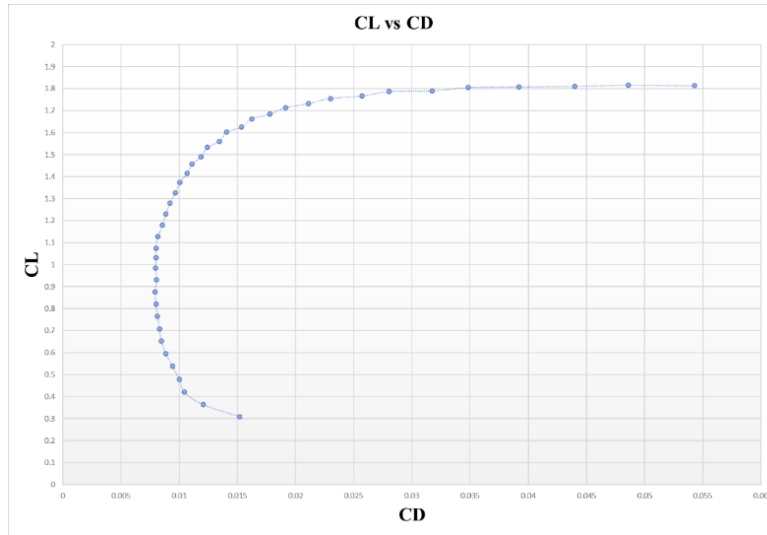


Figure 2 Airfoil polar at 70km/h

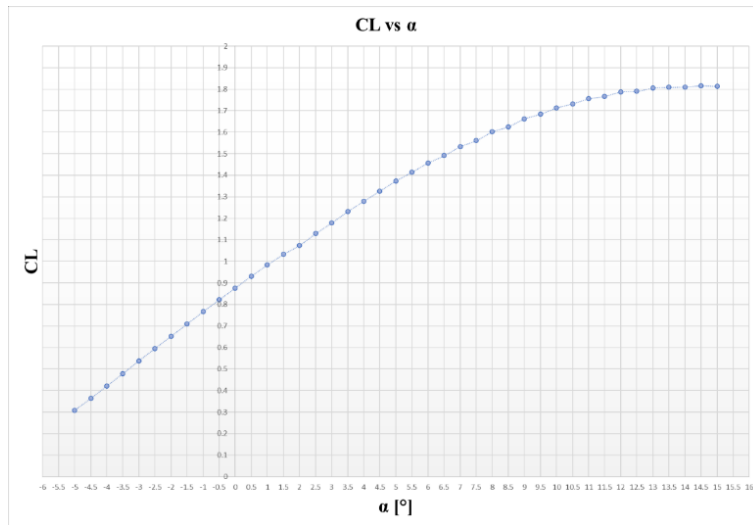


Figure 3 Airfoil lift curve at 70 km/h

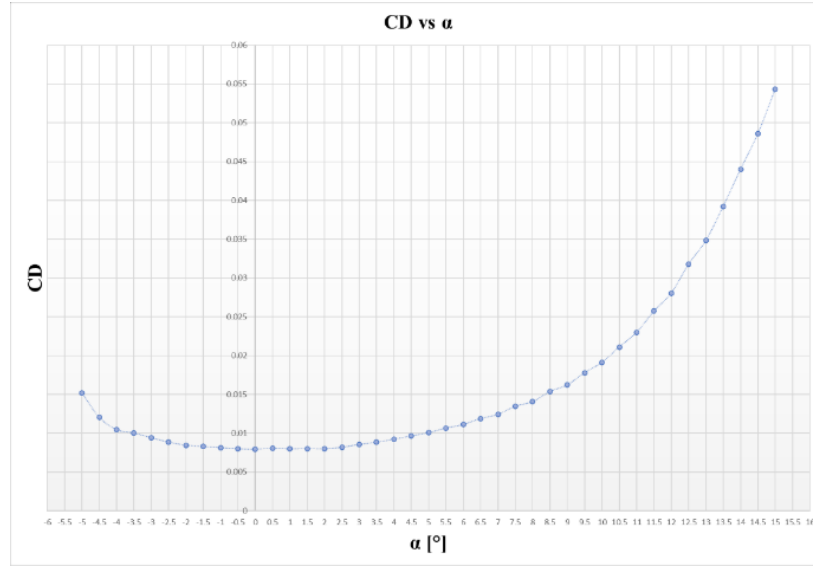


Figure 4 Drag curve at 70 km/h

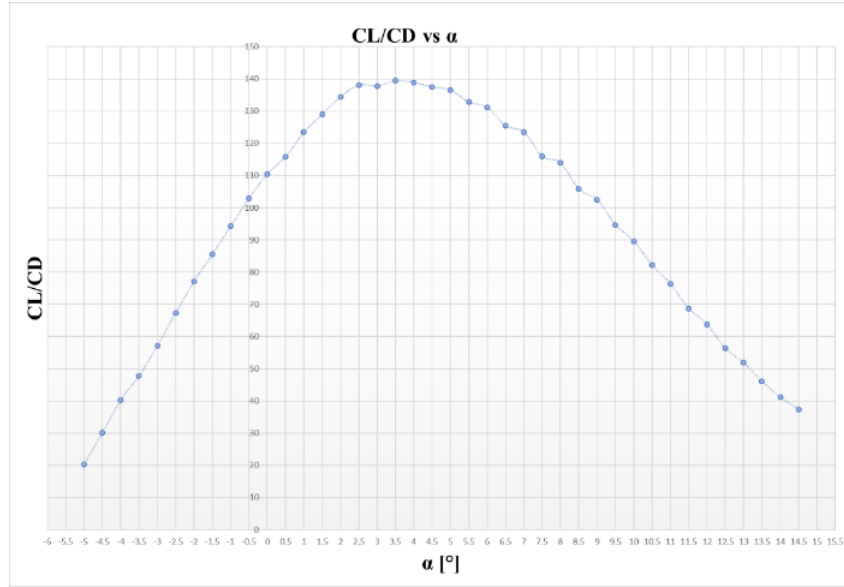


Figure 5 Lift-to-Drag ratio (L/D) vs. Angle of Attack at 70 km/h

For the rectangular wing geometry, the following characteristics were considered: chord $c = 0.4$ m and wingspan $b = 2.5$ m. Based on these data, the lifting surface area can be calculated as follows:

$$S \approx 0.98 \text{ m}^2 \quad (4)$$

And the wing aspect ratio is given by:

$$AR = \frac{b^2}{S} = 6.37 \quad (5)$$

The total UAVs mass is approximately $m=25$ kg, which corresponds to the weight:

$$G = m \cdot g = 245.25 \text{ N} \quad (6)$$

For performance evaluation, the following assumptions were adopted: parasitic drag coefficient $C_{D0} = 0.035$, Oswald efficiency factor $e = 0.85$, and air density $\rho = 1.225 \text{ kg/m}^3$, which leads to the induced drag constant:

$$k = \frac{1}{\pi \cdot e \cdot AR} = 0.0587 \quad (7)$$

For the preliminary calculations, values of $C_{D0} = 0.035$ and $e = 0.85$, specific to small fixed-wing UAVs, were used. These values were selected based on the typical ranges reported in the specialized literature [44,45], corresponding to configurations with moderate lifting surfaces and rectangular planforms.

Considering the use of the MH 114 airfoil, the maximum lift coefficient is approximately $C_{L_{max}} = 1.4$. Thus, the air speed at which the wing generates sufficient lift to support the UAV's weight can be determined.

$$V_{stall} = \sqrt{\frac{2 \cdot G}{\rho \cdot S \cdot C_{L_{max}}}} = 17.08 \text{ m/s} \quad (8)$$

In order to achieve the maximum lift-to-drag ratio $(L/D)_{max}$, the following condition applies:

$$C_L^* = \sqrt{\frac{C_{D0}}{k}} = 0.772 \quad (9)$$

Therefore, the velocity corresponding to the previously mentioned condition results as:

$$V_{(L/D)_{max}} = \sqrt{\frac{2 \cdot G}{\rho \cdot S \cdot C_L^*}} = 23.005 \text{ m/s} \quad (10)$$

The maximum lift-to-drag ratio can be written as follows:

$$\left(\frac{L}{D}\right)_{max} = \frac{C_L^*}{2 \cdot C_{D0}} = 11.02 \quad (11)$$

3.2. Preliminary conclusions on Aerodynamic Stability

Based on the theoretical aerodynamic calculations and the validated polar curves for the main lifting surface at the target cruise regime, several preliminary conclusions regarding the platform's stability can be formulated:

- **Inherent Longitudinal Stability:** The theoretical validation of the MH 114 reflex airfoil at the operational Reynolds number ($Re \approx 5.3 \times 10^5$) confirms its optimal behavior for this UAV configuration. The geometry's inherent characteristic, a near-zero or slightly positive pitching moment ($C_m \approx +0.02$), provides natural auto-stability on the pitch axis.
- **Equilibrium and Trim Drag Minimization:** Because the selected aerodynamic profile does not generate the strong nose-down pitching moments typical of classic cambered airfoils, the aircraft requires significantly less

downward balancing force from the empennage. This condition not only ensures robust static longitudinal stability but also drastically reduces the trim drag penalty during steady-state cruise.

- **Stable Flight Envelope:** The calculated sizing parameters for the rectangular planform ($AR = 6.37$) and the identification of the optimum lift coefficient ($C_L^* = 0.772$) for maximum aerodynamic efficiency ($L/D_{max} = 11.02$) indicate that the UAV will operate well within the linear region of the lift curve. This guarantees predictable aerodynamic responses to pitch variations and prevents sudden loss of stability due to premature flow separation.

In summary, the preliminary analysis demonstrates that the structural and aerodynamic sizing of the main wing establishes a naturally stable and balanced platform, providing a reliable foundation prior to the integration and sizing of the lateral control surfaces.

4. CONTROL SURFACES

The operating mechanism of the ailerons is based on the asymmetric alteration of aerodynamic forces distributed across the wingspan, thereby generating the rolling moment necessary for maneuvering. Their placement at the extremities of the trailing edge is strategic, serving to maximize the moment arm and, implicitly, the control authority. Their actuation is differential: deflecting one surface downward increases the airfoil camber and local lift, while deflecting the opposite one upward reduces lift, creating a rotational couple around the longitudinal axis [46]. The aileron represents the main control surface responsible for an aircraft's roll control, categorized as a primary control surface alongside the elevator and the rudder.

Aileron effectiveness depends directly on their platform area, the maximum deflection angle, and the distance from the aircraft's axis of symmetry. During the sizing phase, the analysis of lateral-directional coupling is essential to counteract unwanted side effects generated by induced drag, such as adverse yaw [46].

Furthermore, advanced design takes into account aeroelastic phenomena at high speeds, including the risk of flutter. To optimize stability and control responses, modern aircraft may integrate ailerons with spoileron-type systems or fly-by-wire technologies, which continuously adjust the control surfaces [46].

From a dynamic standpoint, the aileron functions primarily as a rate control, producing a steady roll rate rather than a fixed bank angle for a constant deflection [46]. The roll response is determined by the balance between the aileron-generated rolling moment and the opposing rolling drag, which becomes increasingly significant for aircraft with large wingspans [46]. Consequently, aileron sizing is usually performed for the most critical low-speed flight condition, where control effectiveness is minimal and handling-quality requirements are most demanding [46].

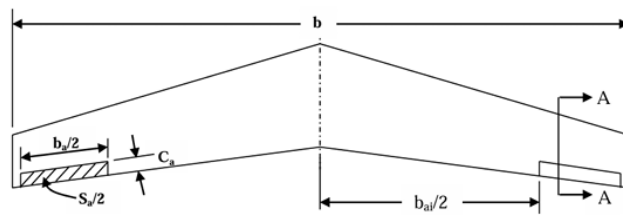


Figure 6 Top-view of the wing and aileron [46]

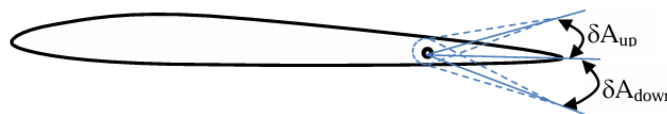


Figure 7 Side-view of the wing and aileron (Section AA) [46]

The design process for an aileron requires the definition of four primary parameters: the planform area (S_a), the chord and span characteristics (C_a/b_a), the maximum upward and downward deflection angles (δ_{Amax}), and the spanwise location of the inboard edge (b_{ai}). As illustrated in Figure 6, standard engineering guidance suggests specific statistical ranges for these values [46]:

$$\frac{S_a}{S} = 0.05 \dots 0.1 \Rightarrow S_a = 0.0343 \text{ m}^2 \quad (12)$$

$$\frac{b_a}{b} = 0.2 \dots 0.3 \Rightarrow b_a = 0.325 \text{ m} \quad (13)$$

$$\frac{C_a}{c} = 0.15 \dots 0.25 \Rightarrow C_a = 0.08 \text{ m} \quad (14)$$

$$\frac{b_{ai}}{b} = 0.6 \dots 0.8 \Rightarrow b_{ai} = 0.91 \text{ m} \quad (15)$$

$$\delta_{Amax} = \pm 30^\circ \quad (16)$$

4.1. Aileron Design Constraints

According to the metrology presented in [46], the design of ailerons is not limited to geometric sizing but involves fundamental physical constraints that affect aircraft controllability. The following aspects have been analyzed and applied to the UAV configuration:

4.1.1. Aileron Effectiveness and Deflection Limits

Aileron effectiveness (τ) is the measure of the control surface's ability to produce the desired rolling moment. As stated in [46], the aileron functions as a rate control device, continuously varying the roll angle (P).

- The constraint: While a larger deflection theoretically generates a larger moment, the text specifies that effectiveness diminishes at high angles due to airflow separation over the control surface.
- Optimization: Following the standard recommendations in the text, typical deflection angles are limited to the range of $\pm 20^\circ$ to $\pm 25^\circ$. For this study, although the mechanical limit is set to 30° , efficient operation is considered to be within the linear region of the $C_l - \delta_a$ curve, avoiding the control surface "stall" zone, which would generate excessive Drag without control benefits.

4.1.2. Adverse Yaw

Adverse yaw is defined as a major side effect where the aircraft tends to yaw in the direction opposite to the commanded turn.

- Physical Cause: The downward-deflected aileron (on the rising wing) induces an increase in lift and, implicitly, a significant increase in Induced Drag (D_i). Conversely, the upward-deflected aileron reduces lift and induced drag.

4.1.3. Aeroelasticity: Aileron Reversal

Aileron Reversal is an aeroelastic effect that occurs at high speeds.

- Mechanism: Deflecting the aileron downward produces a local pitching moment that twists the wing structure, reducing the local angle of attack.
- Constraint: If the wing's torsional stiffness is insufficient, this twisting (structural washout) reduces lift more than the aileron increases it, effectively reversing the pilot's command.

- Design requirement: To prevent this, the wing structure (Spar/Skin combination) is designed such that the structural reversal speed (V_{rev}) is significantly higher than the maximum operational speed (V_{max}) of the UAV.

5. LATERAL CONTROL AUTHORITY AND AILERON SIZING ANALYSIS

The primary objective of this section is to validate the lateral maneuverability of the UAV by analyzing the rolling moment (M_x) and the resulting roll angular acceleration ($\ddot{\phi}$) generated by the aileron deflection. The aileron sizing process was conducted to ensure sufficient control authority during the cruise phase, considering the specific mass distribution and aerodynamic characteristics of the tandem-wing configuration [46].

5.1. Calculation Methodology

To bridge the gap between the two-dimensional computational data and the three-dimensional dynamic response of the aircraft, a hybrid analytical-computational approach based on Strip Theory was employed. Performing a full 3D CFD simulation of the entire wing for every possible aileron deflection angle incurs prohibitive computational costs. Therefore, the numerical simulations were constrained to 2D domains to accurately capture the local section lift coefficient variation (ΔC_l), while Strip Theory integrates this aerodynamic contribution over the aileron's spanwise location. The mathematical model assumes a linear relationship between the control surface deflection and the change in the lift coefficient within the unstalled range. The calculations are based on the following fundamental equations derived from standard flight dynamics principles [19, 46]:

- Dynamic Pressure (q): the dynamic pressure is calculated for the cruise velocity (V) at standard sea level air density (ρ):

$$q = \frac{1}{2} \rho V^2 \quad (17)$$

- Aileron Rolling Moment Coefficient (ΔC_L): The effectiveness of the aileron is determined by the differential change in the lift coefficient (ΔC_L) produced by the deflection angle (δ), relative to the neutral position:

$$\Delta C_L = C_{L(\delta)} - C_{L(0)} \quad (18)$$

- Rolling Moment (M_x): The transition from 2D section data to a 3D aerodynamic rolling moment is achieved by assuming that the outboard wing section behaves as a series of infinitesimally narrow 2D strips. The local incremental lift force generated on a single strip of width dy is defined as $dL = q \cdot c \cdot \Delta C_l \cdot dy$. Since this force acts at a lateral distance y from the aircraft's longitudinal axis of symmetry, the differential rolling moment produced by this strip is $dM_x = y \cdot dL$.

To obtain the total 3D rolling moment (M_x) generated by the aileron, this differential moment is integrated along the spanwise location of the control surface, from its inboard edge (y_{in}) to its outboard edge (y_{out}):

$$M_x = \int_{y_{in}}^{y_{out}} (q \cdot c \cdot \Delta C_l \cdot y) dy \quad (19)$$

Assuming the chord (c) is constant over the aileron span (rectangular planform approximation), the integration yields the final analytical expression [46]:

$$M_x = q \cdot c \cdot \Delta C_l \cdot \frac{y_{out}^2 - y_{in}^2}{2} \quad (20)$$

Where: M_x is the rolling moment, c is the mean aerodynamic chord of the wing at the aileron station, and y_{out}/y_{in} is the spanwise distance to the aileron outboard/inboard edge. This integral method provides a robust estimation of 3D control authority, being highly accurate for wings with moderate to high aspect ratios (such as AR=6.37 for this platform) during preliminary sizing phases.

- Roll Angular Acceleration ($\ddot{\phi}$): The dynamic response of the aircraft is evaluated by relating the generated aerodynamic moment to the aircraft's mass moment of inertia about the longitudinal axis (I_{xx}):

$$\ddot{\phi} = \frac{M_x}{I_{xx}} \quad (21)$$

5.2. Preliminary Conclusions on Analytical Sizing

It should be noted that the present analysis is limited to the estimation of the initial roll angular acceleration derived from the generated aerodynamic rolling moment and the aircraft inertia. A complete dynamic roll response evaluation would require inclusion of roll damping derivatives (Cl_p), yaw-roll coupling effects (Cl_β , Cnr), and time-domain integration of the lateral-directional equations of motion. Such a dynamic handling-quality assessment, including bank angle response over time and control damping characteristics, is beyond the scope of the current preliminary design study and will be addressed in future work through full 6-DOF simulation.

The theoretical framework established for the lateral control authority confirms that the strip theory approach provides a robust analytical foundation for predicting the UAV's rolling moment and angular acceleration. By mathematically defining the linear relationship between aileron deflection, local lift increments, and the aircraft's moment of inertia, this methodology allows for the precise preliminary sizing of the outboard control surfaces. Consequently, these analytical formulations establish the necessary baseline parameters and equations required to process the aerodynamic coefficients that will be extracted from the subsequent computational fluid dynamics (CFD) analysis.

6. CFD ANALYSIS

The analysis was performed for standard cruise conditions using geometric and inertial parameters extracted from the CAD model. The specific input values used in the simulation are listed below:

Table 2 Input values

Cruise Velocity	$V = 19.44 \text{ m/s}$
Air density	$\rho = 1.225 \text{ kg/m}^3$
Dynamic pressure	$q = 231.56 \text{ Pa}$
Roll Moment of Inertia	$I_{xx} = 3.44 \text{ kg} \cdot \text{m}^2$

6.1. Case Setup

To determine the moment of inertia associated with the aileron, CFD analysis was performed. In this analysis, the aileron was rotated through an angular range from -12° to $+12^\circ$ to evaluate the corresponding lift coefficient (C_L). The obtained lift coefficient data were subsequently used to compute the aerodynamic moment acting on the aileron and, implicitly, its moment of inertia. The CFD simulations were conducted using ANSYS Fluent 2023 R2, while the aileron geometry was modeled in SolidWorks 2024.

The CFD analysis was performed as a two-dimensional simulation. Figure 8 illustrates the definition of the computational domain, including the applied boundary conditions and the corresponding domain dimensions. These specifications were selected to ensure an accurate representation of the flow field around the aileron while minimizing boundary interference effects on the aerodynamic results.

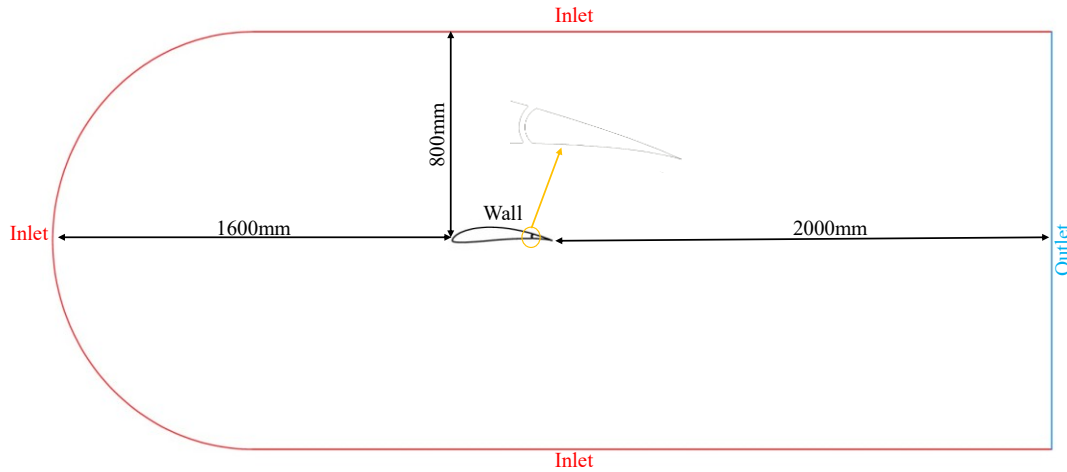


Figure 7 Computational domain and boundary conditions for the 2D CFD analysis of the aileron

Figure 8 presents the two-dimensional computational domain employed for the CFD analysis, together with the applied boundary conditions and domain dimensions. The domain extends 1600 mm upstream of the aileron leading edge and 2000 mm downstream of the trailing edge, ensuring sufficient development of the flow and minimizing outlet boundary effects. In the vertical direction, the domain height is 800 mm, providing adequate clearance to limit blockage and confinement effects.

A velocity inlet boundary condition was imposed at the upstream and curved lateral boundaries, with a uniform inlet velocity of 19.44 m/s. The domain dimensions were selected based on established CFD best practices for external aerodynamics, ensuring that the airfoil is located sufficiently far from the upper and lower boundaries to avoid blockage effects. The vertical distance corresponds to more than 3 chord lengths, which exceeds standard recommendations in the literature. Therefore, boundary-induced errors are expected to be negligible. The downstream boundary was defined as a pressure outlet, with the relative static pressure set to 0 Pa, allowing the flow to exit the domain without artificial constraints. The aileron surface was modeled as a no-slip wall, enforcing zero velocity at the solid boundary to accurately capture boundary layer development and aerodynamic forces. These boundary conditions and domain dimensions were selected to ensure reliable prediction of the lift coefficient and associated aerodynamic moments over the investigated deflection range.

The computational grid was generated using the ANSYS Workbench Mesher. A hybrid mesh topology was adopted, consisting predominantly of hexahedral elements, complemented by triangular elements in regions of complex geometry. The mesh was locally refined in the vicinity of the airfoil and aileron surfaces to accurately resolve near-wall flow effects and boundary layer phenomena, while a coarser discretization was employed in the far-field to limit the overall computational cost.

To ensure adequate near-wall resolution when using the $k-\omega$ SST turbulence model, a target wall-normal resolution of $y^+ \approx 1$ was imposed. The Reynolds number was computed based on the free-stream velocity and the characteristic chord length according to

$$Re = \frac{\rho U_{\infty} c}{\mu} \quad (22)$$

which, for $U_{\infty} = 19.44$ m/s, $\rho = 1.225$ kg/m³, $\mu = 1.82 \times 10^{-5}$ Pa · s and, $c = 0.4$ m, yields $Re \approx 5.3 \times 10^5$.

The skin-friction coefficient was estimated using a turbulent flat-plate correlation,

$$C_f = \frac{0.0576}{Re^{1/5}} \quad (23)$$

from which the friction velocity was determined as

$$u_\tau = U_\infty \sqrt{\frac{C_f}{2}} \quad (24)$$

The required height of the first inflation layer was then calculated using the standard wall-unit relation,

$$y_1 = \frac{y^+ \mu}{\rho u_\tau} \quad (25)$$

For a target value of $y^+ = 1$, the resulting first-layer height was on the order of 1.7×10^{-5} m.

To conservatively ensure accurate boundary layer resolution, a first-layer height of 1×10^{-5} was prescribed in the final mesh. Inflation layers were applied along the airfoil and aileron surfaces with a maximum of 25 layers and a growth rate of 1.2. This meshing strategy enables proper resolution of the viscous sublayer and the logarithmic region of the boundary layer, thereby improving the fidelity of the predicted aerodynamic forces and moments.

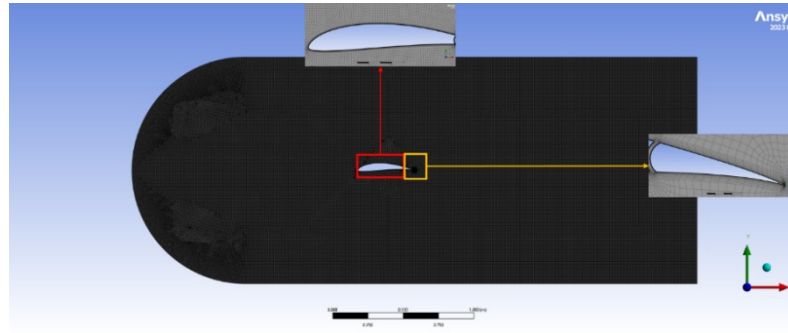


Figure 8 Hybrid computational mesh and near-wall refinement around the aileron and airfoil

A detailed view of the mesh around the aileron is highlighted in figure 9, emphasizing the refined near-wall region and the applied inflation layers along the airfoil and aileron surfaces. This local refinement ensures adequate resolution of the boundary layer and wake development. Additional close-up views of the leading and trailing edge regions are provided to demonstrate the mesh quality and smoothness in areas characterized by strong pressure gradients and flow curvature. The adopted meshing strategy supports accurate prediction of aerodynamic forces and moments across the investigated range of aileron deflection angles.

Although the mesh was generated following established best practices for external aerodynamic simulations, ensuring adequate near-wall resolution and local refinement in high-gradient regions, a formal grid convergence study was not conducted in the present work. The selected mesh density was deemed sufficient for capturing sectional aerodynamic trends and comparative control effectiveness. Nevertheless, it is acknowledged that a systematic grid refinement analysis would further strengthen the numerical validation, and this will be addressed in future investigations.

6.2. Results and analysis

All simulations were performed for a maximum of 1000 iterations. Convergence was assessed based on the residuals of all governing equations, which were required to decrease and stabilize below a threshold value of 10^{-7} , ensuring numerical convergence of the solution.

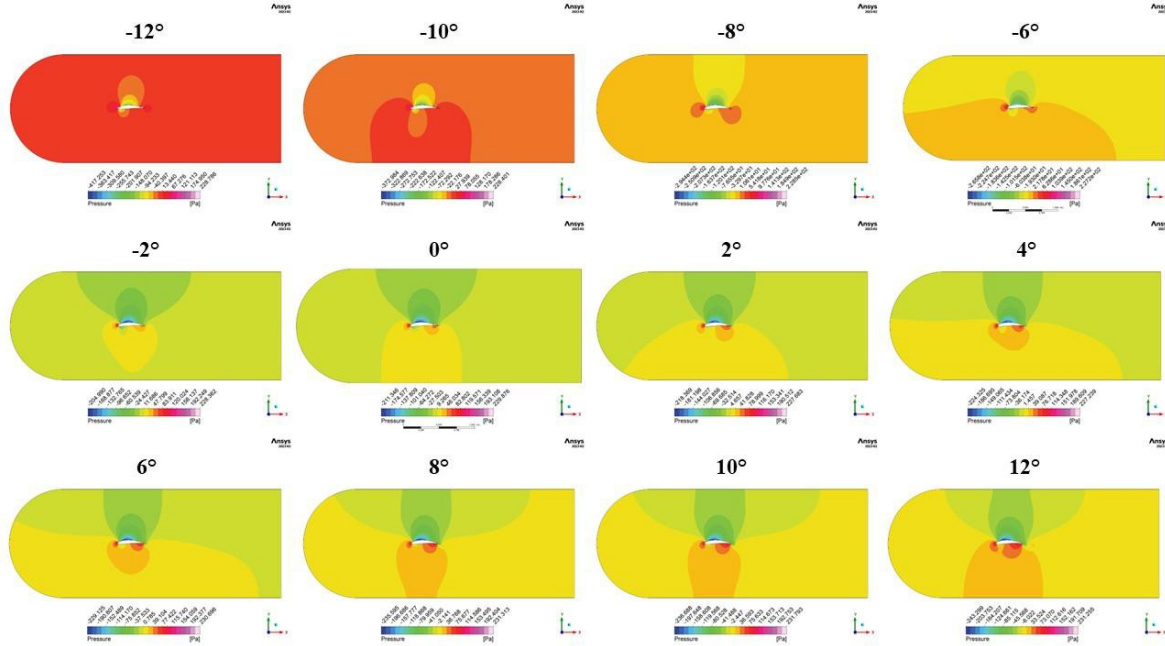


Figure 9 Static pressure contours around the aileron for deflection angles from -12° to $+12^\circ$

Figure 10 presents the static pressure contour distributions obtained from the CFD simulations for aileron deflection angles ranging from -12° to $+12^\circ$, in increments of 2° . The pressure fields clearly illustrate the evolution of the aerodynamic loading on the aileron as a function of deflection angle.

For negative deflection angles (-12° to -2°), a region of elevated pressure is observed on the upper surface of the aileron, accompanied by a corresponding low-pressure region on the lower surface. This pressure distribution results in a downward aerodynamic force, consistent with negative lift generation. As the deflection angle approaches 0° , the pressure field becomes more symmetric about the aileron, indicating a near-zero net lift condition.

For positive deflection angles (2° to 12°), the pressure distribution progressively inverts, with a pronounced low-pressure region developing on the upper surface and a high-pressure region forming on the lower surface of the aileron. The magnitude and spatial extent of these pressure gradients increase with deflection angle, leading to a corresponding increase in lift force and aerodynamic moment. Additionally, stronger pressure gradients and wake structures are observed in the downstream region at higher deflection angles, indicating increased flow acceleration and aerodynamic loading.

Overall, the pressure contour plots demonstrate a consistent and physically coherent variation of the flow field with aileron deflection, validating the numerical setup and providing the basis for subsequent lift coefficient and moment calculations.

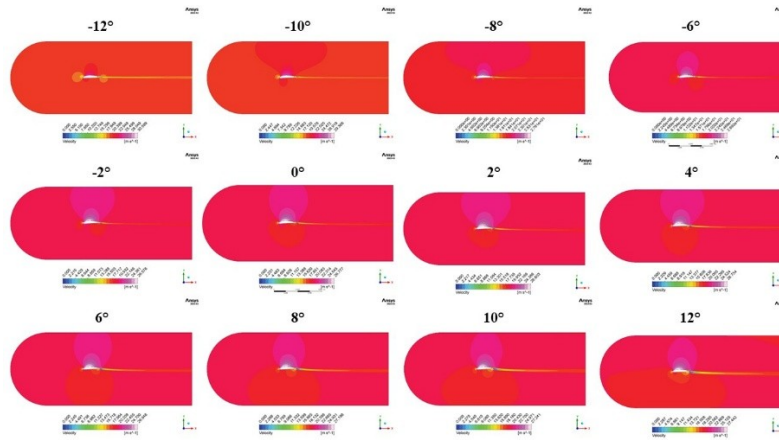


Figure 10 Velocity magnitude contours around the aileron for deflection angles from -12° to $+12^\circ$

Figure 11 illustrates the velocity magnitude contours obtained from the CFD simulations for aileron deflection angles ranging from -12° to $+12^\circ$, with increments of 2° . The velocity fields provide insight into the acceleration, deceleration, and wake characteristics of the flow as a function of aileron deflection.

For negative deflection angles (-12° to -2°), the flow accelerates predominantly along the lower surface of the aileron, while reduced velocities are observed on the upper surface. This behavior is consistent with the pressure distributions presented previously and results in negative lift generation. A relatively thin and attached wake is observed downstream of the aileron, indicating stable flow conditions within this deflection range.

At zero deflection (0°), the velocity distribution becomes nearly symmetric about the aileron, with comparable acceleration on both surfaces and a narrow wake aligned with the free-stream direction. This configuration corresponds to a near-zero net aerodynamic force.

For positive deflection angles (2° to 12°), a pronounced acceleration of the flow develops over the upper surface of the aileron, accompanied by a region of reduced velocity on the lower surface. The velocity gradients intensify with increasing deflection angle, leading to higher local flow speeds and a more energetic wake downstream. At larger positive deflections, the wake becomes thicker and more inclined relative to the free stream, reflecting the increase in aerodynamic loading and flow turning induced by the aileron.

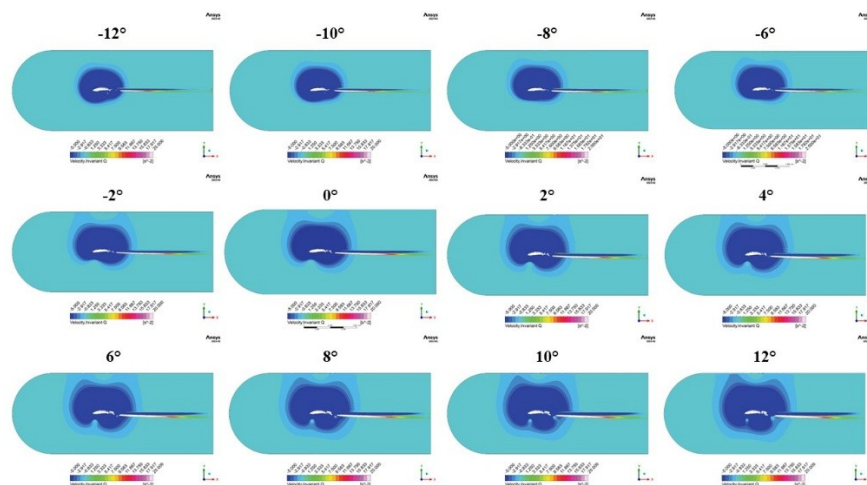


Figure 11 .Q-criterion (velocity invariant Q) contours for aileron deflection angles between -12° and $+12^\circ$

Figure 12 illustrates the spatial distribution of the Q-criterion for all investigated aileron deflection angles, providing a qualitative visualization of vortical structures and regions where rotational motion dominates over strain. The Q-criterion is particularly useful for identifying coherent vortices and wake dynamics generated by the aileron.

At large negative deflections (-12° to -8°), the contours reveal a compact vortical region forming immediately downstream of the aileron, accompanied by a relatively narrow wake. The intensity of the Q-invariant in these cases indicates localized rotational flow, primarily associated with shear layer development at the trailing edge. As the deflection angle approaches zero, the vortical region becomes more symmetric with respect to the aileron chord, and the wake remains well aligned with the free-stream direction, suggesting stable and attached flow conditions.

For positive deflection angles (2° to 12°), the Q-criterion highlights a progressive growth and downstream elongation of the vortical structures. The regions of elevated Q-values expand and shift in accordance with the increased flow turning imposed by the aileron, reflecting stronger shear layers and enhanced wake development. At higher positive deflections, the wake becomes more pronounced and spatially extended, indicating increased aerodynamic loading and intensified rotational effects in the flow.

Overall, the Q-invariant contours demonstrate a clear dependence of the flow topology on aileron deflection angle. These results complement the pressure and velocity analyses by providing additional insight into wake structure evolution and vortex formation mechanisms, supporting the interpretation of the aerodynamic forces and moments obtained from the simulations.

The present evaluation of aileron effectiveness is based exclusively on two-dimensional CFD simulations. While this approach accurately captures sectional lift increments caused by control surface deflection, rolling behavior of a finite wing ($b = 2.5$ m, $AR = 6.37$) is inherently three-dimensional and influenced by induced effects, spanwise load redistribution, and wingtip vortices.

The global rolling moment was estimated by extrapolating sectional lift increments using classical preliminary design assumptions. However, this method neglects spanwise aerodynamic coupling and nonlinear finite-wing corrections. Given the moderate aspect ratio of the UAV wing, these effects may introduce deviations from the predicted rolling performance.

Consequently, the present results should be interpreted as a first-order control effectiveness assessment. Future work will include three-dimensional CFD simulations and/or experimental validation to quantify finite-wing corrections and refine the rolling moment estimation.

The CFD study investigated aileron deflection angles ranging from -12° to $+12^\circ$. Based on the numerical simulations, the lift coefficient (C_L) of the aileron was computed for each deflection angle, with the resulting values reported in the second column of Table 2.

Table 3 Simulation results

$\delta [^\circ]$	$C_L [-]$	$M_x [Nm]$	$\ddot{\phi} [rad/s^2]$
-12	-0.00312495	-30.6153	-8.899797
-10	0.004294092	-24.5136	-7.126041
-8	0.015870543	-14.9926	-4.358326
-6	0.019461554	-12.0392	-3.499782
-4	0.025112932	-7.39133	-2.148642
-2	0.030312085	-3.11533	-0.905620
0	0.0341	0	0.000000

2	0.042673834	7.051467	2.049845
4	0.046607439	10.28662	2.990297
6	0.051011492	13.90869	4.043225
8	0.052806158	15.3847	4.472296
10	0.056128697	18.11729	5.266654
12	0.057696387	19.40662	5.641460

- **Control Authority and Dynamic Response:** The calculated maximum angular acceleration ranges between 5.64 rad/s^2 and 8.90 rad/s^2 . According to standard handling qualities criteria for UAVs, these values indicate that the aircraft possesses sufficient control authority. While the response is not aggressive, an acceleration approximately 9 rad/s^2 ensures that the aircraft remains responsive to pilot inputs and can effectively reject external disturbances (such as gusts) during the cruise phase.
- **Aerodynamic Asymmetry:** The data reveals a distinct asymmetry in control effectiveness, which is visually emphasized in the lateral control authority graph in Figure 13. The upward deflection (negative angle) generates a rolling moment (-30.62 Nm) compared to the downward deflection (+19.41 Nm) for the same deflection angle (12°).
 - **Efficiency Ratio:** The upward deflection is approximately 57% more effective in generating roll torque than the downward deflection.
 - This asymmetry is advantageous for flight dynamics. The increased drag associated with the "up-going" aileron (which produces the higher roll moment) helps counteract the adverse yaw moment naturally generated during a turn, thereby reducing the workload for the directional control system (rudder) [19, 46].
- **Non-linear Aerodynamic Effectiveness:** The graphical representation (Figure 14) of the aileron lift coefficient (C_L) versus deflection angle further details this aerodynamic behavior. At the neutral position (0°), the local C_L is approximately 0.034, corresponding to the baseline lift of the cruise configuration. For negative deflections (trailing edge up), the lift drops sharply and consistently. However, for high positive deflections (beyond $+8^\circ$), the curve begins to flatten. This flattening trend indicates a gradual reduction in control surface effectiveness, likely caused by boundary layer thickening and the early onset of flow separation on the upper surface when the aileron is deflected downward at steep angles.

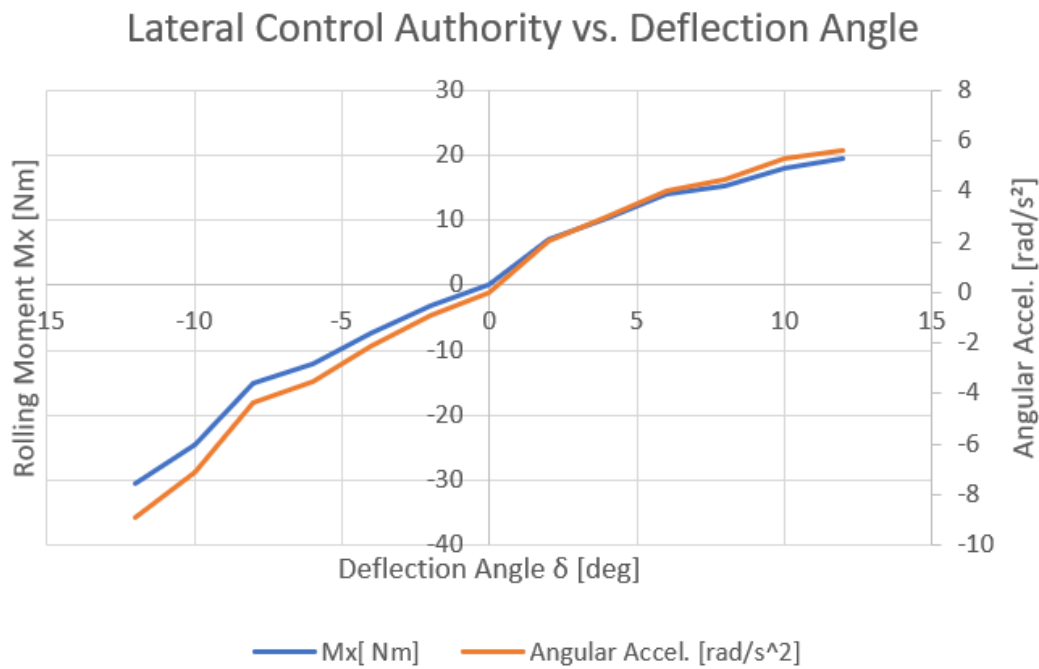


Figure 12 Lateral Control Authority vs. Deflection Angle

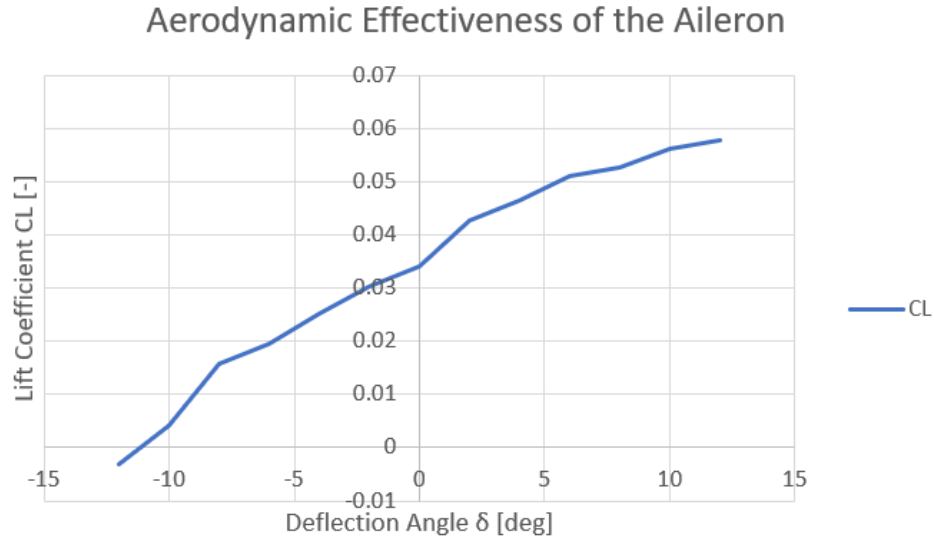


Figure 13 Aerodynamic Effectiveness of the Aileron

7. CONCLUSIONS

The research and design activities carried out for the fixed-wing assembly of the hybrid VTOL UAV resulted in a configuration tailored to the specific operational constraints of hybrid VTOL platforms operating in low-Reynolds-number flight regimes. The final design integrates aerodynamic performance, structural robustness, and control effectiveness into a unified platform suitable for long-endurance missions. In this context, CFD analyses played a central role in validating and refining the aerodynamic behavior of both the lifting surfaces and control elements.

The selection of the MH 114 reflex airfoil was confirmed through a combination of theoretical considerations and CFD results, demonstrating its suitability for reconciling the high-lift demands of the hover and transition phases with the low-drag requirements of cruise. The numerical simulations indicate that the airfoil maintains favorable pressure distributions and extended regions of attached flow at the investigated Reynolds numbers, while exhibiting near-neutral pitching moment characteristics ($C_m \approx 0$). These features contribute to inherent longitudinal stability and reduced trim drag, which are essential for efficient cruise performance. From a structural standpoint, the proposed hybrid construction, comprising birch wood ribs and aluminum spars enclosed within a composite skin, was shown to preserve the intended aerodynamic profile and provide sufficient torsional stiffness to mitigate aeroelastic risks such as flutter.

With respect to lateral control and maneuverability, the aileron design was developed following established sizing methodologies and subsequently assessed using CFD simulations. Key geometric parameters, including planform area (S_a), chord (C_a), and span (b_a), were defined to ensure adequate rolling moment authority across the full deflection range. The rectangular planform and outboard placement were selected to maximize the rolling moment arm, while CFD analyses of pressure, velocity, and vortical structures confirmed the effectiveness of the aileron in generating the required lift increments and control moments without inducing adverse flow separation.

In conclusion, the proposed fixed-wing configuration represents a robust and well-validated engineering solution for hybrid VTOL UAV applications. By combining low-Reynolds-number aerodynamic design with CFD-based validation of lifting surfaces and control effectiveness, the resulting platform satisfies the operational requirements for stability, endurance, and payload capacity, while maintaining manufacturability and structural integrity.

Regarding future research directions, subsequent phases of this project will focus on the experimental validation of the computational data through targeted wind tunnel testing and flight-test telemetry of a physical prototype. Furthermore, comprehensive 6-degree-of-freedom (6-DOF) dynamic simulations will be conducted to formally evaluate the closed-loop handling qualities, aircraft roll response over time, and the transient aerodynamic behavior during the critical VTOL-to-cruise transition phase.

ACKNOWLEDGEMENT

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AUTOMATION AND CONTROL SYSTEM FOR THE REVAMPING OF A NATURAL GAS COMPRESSOR STATION

Sebastian DINU^{1,2}, Dragoş NEACŞU¹, Adrian SĂVESCU¹, Georgeta Mihai^{1,*}, Khurram AFZAAL³

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Corresponding author: georgeta.mihai@comoti.ro

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ABSTRACT: The original automation system of the Stoeneşti gas compression station became obsolete, leading to reduced maintainability, operational difficulties, and increased downtime. To address these issues, this article presents the complete revamping process of the station, with the primary objective of modernizing its automation architecture. The implemented solution consists of redesigning the control cabinets, integrating modern human-machine interfaces (HMIs), and developing updated software for the four electrically driven twin-screw compressors operating in a two-stage process. The implementation of the new control logic and HMI architecture resulted in a stable discharge gas pressure of 25-26 bar, enabling the station to consistently meet its rated flow rate of 50.000 Nm³ per day. Furthermore, the transition from manual component testing to integrated digital diagnostics on the operator panels has significantly reduced troubleshooting time and improved overall system availability. These improvements ensure the reliable integration of the station into the regional gas distribution network.

KEYWORDS: Industrial Automation, Twin-Screw Compressors, Supervisory Control and Data Acquisition, Gas compression.

NOMENCLATURE

HMI – Human-Machine Interface;

I/O – Input/Output;

PLC – Programmable Logic Controller;

SCADA – Supervisory Control and Data Acquisition;

UPS – Uninterruptible Power Supply;

USB – Universal Serial Bus;

VDC – Volts Direct Current.

¹ Romanian Research and Development Institute for Gas Turbines COMOTI, Romania.

² National University of Science and Technology Politehnica Bucharest, Romania.

³ Systems Limited, Lahore, Pakistan.

*Corresponding author: georgeta.mihai@comoti.ro

1. INTRODUCTION

Industrial automation plays a key role in ensuring safe, reliable and efficient operation of modern industrial processes. Advancements in control hardware, software platforms and human-machine interfaces have significantly improved monitoring, diagnostics and operational decision-making in industrial processes [1–4].

Twin-screw electro-compressors [5–7] use two helical rotors rotating in opposite directions. Modern manufacturing techniques allow for high efficiency, also increasing sensitivity to thermal expansion and mechanical interference, making monitoring and control systems essential to prevent rotor contact and mechanical failure.

The Stoenеști compression station (Fig.1) comprises four screw-electro compressors delivering compressed natural gas at pressures of up to 30 bar and a rated flow rate of approximately 50.000 Nm³ per day [8]. The compressed gas supplies the surrounding communes and a main gas distributor's pipeline. The gas compressors [9], designed and installed by COMOTI between 2009 and 2010, were originally equipped with an automation system that became increasingly difficult to maintain. Starting in 2020, key automation components such as PLCs, communication modules, and HMI devices became obsolete and were no longer manufactured. This created a specific engineering problem characterized by reduced maintainability, significantly longer troubleshooting times, and increased downtime. Furthermore, the legacy system could no longer meet the modern requirements for SCADA interoperability. To address this gap, a complete revamping of the automation system was necessary, which was requested by the beneficiary and realized in 2025. The revamping included the redesign of the control cabinets and the installation of modern operating panels for each compressor.

Unlike standard automation revamping projects that often focus on simple one-to-one hardware replacement, the approach at the Stoenеști station is unique due to the development of a synchronized control logic for its paired, two-stage compression architecture. The novelty of this implementation consists in creating a custom interlocking framework that manages the K1-K3 and K2-K4 pair as a single, coordinated functional system. This software logic manages the startup of the first stage and the automatic synchronization of the second stage as a single, coordinated process. This ensures a higher level of operational safety for the compressor pairs, providing a custom engineering solution that offers more than a typical automation replacement.

Under these conditions, a complete revamping of the automation system was necessary. The main objectives were to redesign the control cabinets, modernize the software architecture, implement intuitive operator interfaces and ensure compatibility with the beneficiary's SCADA system [10, 11]. The upgraded automation system provides the necessary safety, monitoring, control and communication functions while also enabling data acquisition for further analysis.

The screw electro-compressors automation system developed at the Stoenеști station offers several advantages not only for the station personnel to monitor and control the industrial process but also to the maintenance teams to streamline diagnostics and fault detection during the station operation.

The main aspect discussed in this article is the revamping process, finalized in October 2025, with a focus on the software solution implemented and the redesigning of the automation cabinets for each compressor, making them compliant with the new interface standard with the operator and communication with OMV Petrom beneficiary's SCADA system.



Fig. 1. Stoenеști gas compression station

2. IMPLEMENTATION OF THE REVAMPED AUTOMATION SYSTEM

The previous automation system was defective and featured a small, unreliable display, making the monitoring process non-intuitive. Consequently, defect isolation was cumbersome and required multiple physical diagnostics directly on the skid components before the revamp.

In the modernized configuration, each compressor is controlled by an independent VersaMax PLC, which serves as the core of the automation cabinet. The PLC interfaces with field transducers via unified 4-20 mA analog signals and digital I/O channels. Process data is gathered, processed according to the predefined control logic using PAC Machine Edition, and communicated to both the local operating panels and the remote SCADA system via an Ethernet module. Powering the PLC and the auxiliary equipment requires a 24 VDC voltage source [11].

This upgrade includes a complete redesign of the cabinet layout, improved wiring organization, and the integration of modern operator panels. As illustrated in Fig. 2 **Error! Reference source not found.**, this transition significantly enhances user interaction, simplifies maintenance, and reduces troubleshooting time [7].



Fig. 2. a) The four automation cabinets, first and third from left to right b) The interior of one of the modernized automation cabinets

The initial phase involved replacing the existing automation cabinets with custom-built units. These were designed from the ground up to meet specific station requirements, ensuring full compatibility with all equipment to be installed. As illustrated in Fig. 2, each cabinet consists of:

- PLC – incorporates the CPU along with digital and analog I/O modules;
- Ethernet Switch – manages the interconnection of the PLCs, and SCADA interface, and the link between each PLC and its respective operator panel;
- 24 VDC Power Supply – provides power to the PLC and all auxiliary equipment;
- Temperature Adapters – utilized for converting signals from temperature transducers;
- Safety Barriers – ensure electrical circuit protection for installations in hazardous areas;
- Relays – used for signal amplification, enabling low-power control circuits to operate high-power actuators;
- Circuit Breakers – safeguard the system by interrupting the circuit during overloads or short circuits
- Indicator Lamps – provide visual status for all system states (Initialization, Operation, Standby and Emergency Shutdown).

3. HUMAN-MACHINE INTERFACE AND DATA MANAGEMENT

The modern touchscreen panels provide an improved overview of the compression process. The main screen (Fig.3) displays a simplified process diagram, real-time parameters, operating hours, and the current equipment state. Through virtual buttons, operators can navigate to secondary screens detailing parameter legends, alarm thresholds, and historical logs, which significantly aid in maintenance and diagnosis operations [12].

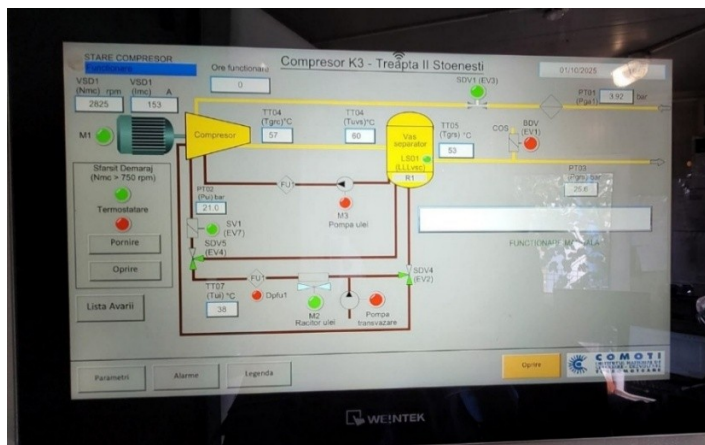


Fig. 3. The operating panel interface for the K3 compressor

Unlike the initial automation system, which lacked data logging capabilities, the revamped configuration allows for continuous recording of process parameters. The panels are configured to log data directly from the PLC to an external USB drive in a format compatible with common spreadsheet software. This USB-based data logging provides reliable backup and serves as a critical tool for maintenance teams. Illustrated in Fig. 4, the extracted data enables precise fault diagnostics and performance optimization of the electro-compressors. Having no previous possibility to acquire data with the old automation system, we could not make a reliable comparison between the operation parameters improvement. Though the average revision and revamping times are in agreement with other installed compressor automation (e.g. Icoana station), we could have a clear idea of the parameters and operation improvement after a longer continuous operation (minimum two years), in order to observe the trends and the necessary revision and overhaul intervals.

1	Date	Time	32-bit Float
2	04-Dec-25	00:00:02	37.680
3	04-Dec-25	00:00:21	43.414
4	04-Dec-25	00:00:41	42.672
5	04-Dec-25	00:01:01	36.070
6	04-Dec-25	00:01:21	30.211
7	04-Dec-25	00:01:41	27.523
8	04-Dec-25	00:02:01	30.836
9	04-Dec-25	00:02:21	37.766
10	04-Dec-25	00:02:41	43.664
11	04-Dec-25	00:03:01	42.633
12	04-Dec-25	00:03:21	36.188
13	04-Dec-25	00:03:41	30.023
14	04-Dec-25	00:04:01	27.352
15	04-Dec-25	00:04:21	30.617
16	04-Dec-25	00:04:41	37.852
17	04-Dec-25	00:05:01	43.727
18	04-Dec-25	00:05:21	42.750
19	04-Dec-25	00:05:41	35.891
20	04-Dec-25	00:06:01	30.180
21	04-Dec-25	00:06:21	27.633
22	04-Dec-25	00:06:41	31.516
23	04-Dec-25	00:07:01	38.609
24	04-Dec-25	00:07:21	44.016
25	04-Dec-25	00:07:41	41.875
26	04-Dec-25	00:08:01	34.859
27	04-Dec-25	00:08:21	29.352
28	04-Dec-25	00:08:41	27.563
29	04-Dec-25	00:09:01	32.406
30	04-Dec-25	00:09:21	39.805
31	04-Dec-25	00:09:41	44.219
32	04-Dec-25	00:10:01	41.148
33	04-Dec-25	00:10:21	33.898

Fig. 4. A sample of logged process data exported for analysis in Microsoft Excel

4. CONTROL LOGIC AND COMPRESSOR OPERATION

The Stoenești compression station's automation system is configured differently from other standard stations, mainly due to the synchronized operation of the compressor pairs. The compressors for both compression stages need to be in suitable operating conditions before they can be started, as seen in Fig. 5.

The starting process is configured in the PLC software as strict step-by-step sequence:

1. Initialization: First, operators must press the unlock buttons on both operating panels to power the motor control center for each compressor.
2. Initial tests: The PLC then automatically checks if there are impediments in initializing the first stage of gas compression.
3. Starting the process: After successfully completing the initial checks, the start button will appear on the operating panels for the first-stage compressors (K1 and K2), allowing the process to be started.
4. Second Stage Synchronization: Once the first-stage compressor's motor (K1 or K2) reaches rated working parameters (750 rpm), the control logic will automatically signal the corresponding second-stage compressor (K3 or K4) to start the second stage compression stage.

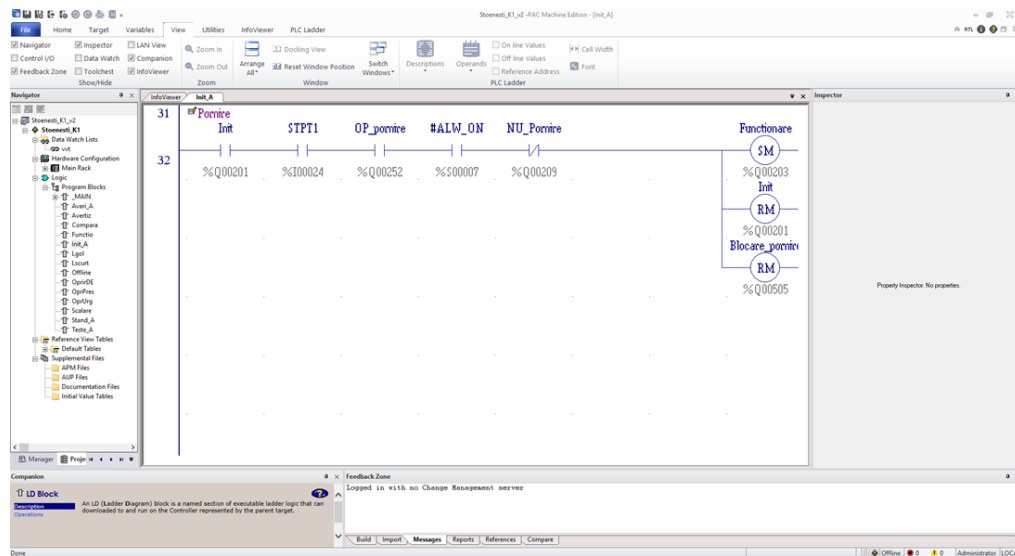


Fig. 5 The software starting sequence for the K1 gas compressor

Should the system detect any anomalies during this sequence, the PLC will initiate an automated shutdown of both compressor stages and display the respective fault message on the corresponding operating panel to aid operators in the troubleshooting process. This ensures that there will always be feedback from the process, using both optical warnings on the operator panel and acoustic failure alarms. Furthermore, in the software program for each PLC, there are preconfigured parameter thresholds that influence the operating mode. When monitored values exceed these predefined limits, the control logic initiates corrective actions or controlled shutdowns, depending on the severity of the deviations. During operation, if either one of the compressors encounters a fault, it will trigger a coordinated shutdown sequence of the entire system, preventing possible damage to the installation.

The interlocking logic serves as a critical safety layer, ensuring that the mechanical integrity of the helical rotors is always protected. These interlocks prevent the system from starting if initial conditions such as oil temperature or suction pressure fall outside the safe operational ranges. The selection criteria for parameter thresholds, such as the 750 rpm synchronization limit or the oil temperature setpoints ("Tui"), are based on the design specifications of the twin-screw compressors to mitigate risks associated with thermal expansion and mechanical interference. By calibrating the logic to trigger either corrective warnings or automated shutdowns based on the severity of these deviations, the system prevents rotor contact and ensures stable gas delivery.

5. ADDITIONAL FEATURES AND PERFORMANCE IMPROVEMENTS

The revamping process of the station introduced several functional enhancements that assist operators in the process of managing the gas compression.

These features are:

- A semi-automatic oil pre-heating system, which can be toggled via a dedicated button on the operating panel.
- An automatic functioning mode for the entire compression installation, allowing for simplified start-stop control.
- An automatic oil cooling system, which adjusts the cooler based on real-time transducer data processed by the PLC.
- An integrated data recording feature, providing a basis for further process analysis and optimization.
- A diagnostic warning and trip system, which displays on-screen messages to ensure faster repairs and easier diagnosis.
- Advanced parameter monitoring, utilizing a dedicated screen to track all variables associated with the compressor.

As seen in Fig. 6 the temperature of the oil that flows through the compressor is kept in normal working thresholds by an efficient automated cooling system that takes the input from the transducer physically placed on the installation (the corresponding parameter on the operator panel is “Tui”) and sends it to the PLC for processing.

The PLC receives this information and executes the corresponding software instructions that adjust the oil cooler depending on the temperature “Tui” value. This ensures an efficient process that keeps the oil temperature according to the thresholds set in the software program and offers visual feedback for station operators.

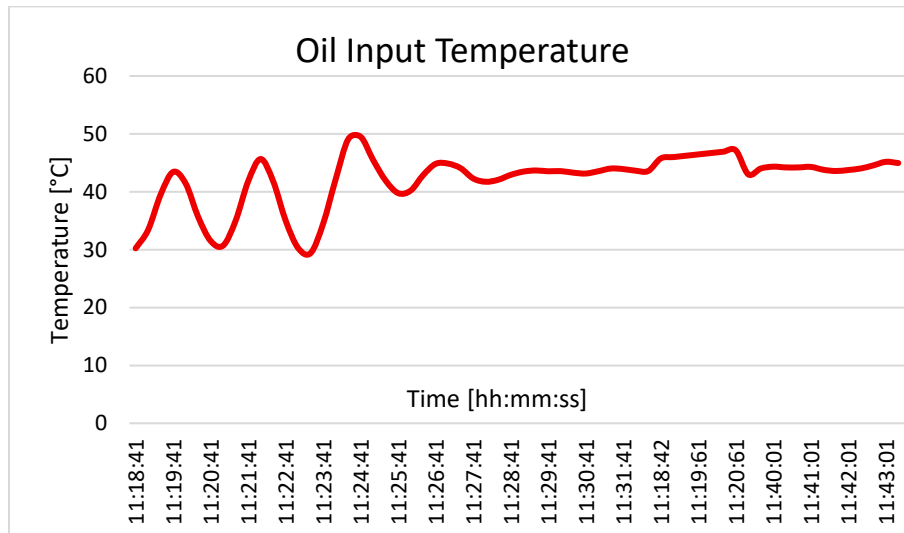


Fig. 6 Evolution of “Tui” parameter – oil temperature entering the K3 compressor

The obsolete sensors and inefficient initial automation system previously affected the station’s production capabilities, making it difficult to meet daily delivery targets. Following the completion of the revamping process, the operational stability and discharge pressure regulation of the compressors have significantly improved. As illustrated in Fig. 7, the system now maintains a stable discharge pressure of approximately 25-26 bar, ensuring better process continuity and a reliable supply of compressed gas to the distribution pipeline.

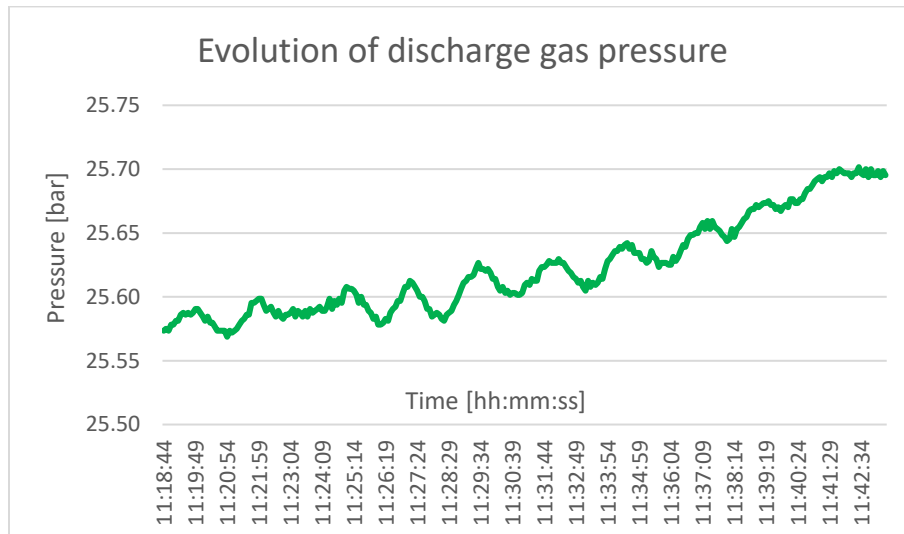


Fig. 7 Evolution of the discharge gas pressure of the K3 compressor

6. CONCLUSIONS

The modernization of the Stoenesti compression station successfully replaced an outdated and difficult to maintain system with a modern automation architecture. By redesigning the control cabinets and implementing updated software, the operational mode of monitoring and controlling the gas compression process has changed dramatically. This transition moved the station from a reliance on physical diagnostics to a modern human-machine interface with integrated alarms and process virtualization.

While this upgrade requires dedicated operator training to accommodate the new functionalities, the revamped system provides significant measurable outcomes. Troubleshooting time has been substantially reduced by transitioning from manual testing of every component to precise digital fault messaging integrated into the HMI. System maintainability is further improved by replacing obsolete PLCs and modules with modular VersaMax architecture, ensuring long-term hardware support.

Furthermore, operator awareness is enhanced through real-time tracking of equipment states, operating hours, and parameter histories directly on the touch screen panels. These technical improvements result in superior operational stability, evidenced by the consistent discharge pressures at 25–26 bar, which ensures the station meets its rated flow rate of 50,000 Nm³ per day. Finally, the modernization allows for seamless SCADA integration, guaranteeing reliable data communication and full compatibility with the beneficiary's system via Ethernet.

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PRELIMINARY COMBUSTION TESTS OF SAF/KEROSENE BLENDS

Andreea MANGRA (PETCU)¹, Marius ENACHE¹, Florin FLOREAN¹, Razvan
CARLANESCU¹

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Corresponding author: andreea.petcu@comoti.ro

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ABSTRACT: Preliminary SAF/kerosene blends combustion tests have been conducted in COMOTI's Combustion Chamber Laboratory on a fire tube that equips a micro gas turbine used as an APU (Auxiliary Power Unit). Given the aviation industry goal of flying with 100% SAF (Sustainable Aviation Fuel), different SAF/kerosene blends have been investigated, with SAF content ranging from 15% to 100%. Due to the available laboratory setup, the combustion campaign has been carried out at atmospheric pressure and constant air flow, varying only the fuel flow. During all tested regimes the following functioning parameters have been monitored: air flow (m³/h), air pressure at combustion chamber inlet (bar), fuel flow (l/min), fuel pressure (bar), exhaust gas temperature (°C). In addition, NO_x, CO, CO₂ and O₂ concentrations in the exhaust gas have been monitored using a gas analyser. A significant decrease of the NO concentration in the exhaust gas has been observed as the SAF content in the fuel mixture increased, while the differences in CO and CO₂ concentrations in the exhaust gas have remained relatively small for all tested fuels. During these preliminary combustion tests no problems in the proper functioning of the used combustion chamber have been observed, even when operating with 100% SAF. Given the limitations of the experimental campaign, the presented findings should be regarded as preliminary comparative data, useful for identifying trends associated with the SAF blending ratio and as a basis for future investigations under more representative engine operating conditions.

KEYWORDS: SAF, combustion tests, exhaust gas analysis, micro gas turbine, fire tube

NOMENCLATURE

APU – Auxiliary Power Unit

ASTM – American Society for Testing and Materials

ATJ – Alcohol-to-Jet

¹ Romanian Research and Development Institute for Gas Turbines COMOTI

FT – Fischer-Tropsch
 HEFA – Hydroprocessed Esters and Fatty Acids
 HFS – Hydroprocessed Fermented Sugars
 HHV – Higher Heating Value
 ICAO – International Civil Aviation Organization
 LHV – Lower Heating Value
 PAH – Polycyclic aromatic hydrocarbon
 SAF – Sustainable Aviation Fuel
 SIP – Synthetic Isoparaffins
 SPK – Synthetic Paraffinic Kerosene

1. INTRODUCTION

Globally, aviation industry is responsible for 2% of all carbon dioxide (CO₂) emissions and 12% of all CO₂ emissions originating from the transportation sector [1]. By 2050, the international aviation industry aims to achieve net zero carbon emissions. One of the most promising short-term solution to achieve this objective is sustainable aviation fuel (SAF). SAF is an alternative fuel made from non-petroleum feedstocks, such as food and yard waste portion of municipal solid waste, woody biomass, oil-based feedstocks (jatropha, camelina, algae), waste animal fats, used cooking greases/ oils [2]. ASTM D7566 Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons dictates fuel quality standards for non-petroleum-based jet fuel and outlines approved SAF-based fuels and the percent allowable in a blend with Jet A. Table 1 presents the ASTM approved SAF production pathways and their corresponding blending limitations.

Table 1. SAF Production pathways approved by ASTM [3]

Pathway	Blending limitation	Feedstocks
Fischer – Tropsch (FT) Synthetic Paraffinic Kerosene (SPK)	50%	Municipal solid waste, agricultural and forest wastes, energy crops
Hydroprocessed Esters and Fatty Acids (HEFA)	50%	Oil-based feedstocks (jatropha, algae, camelina)
Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (HFS – SIP)	10%	Sugars (cellulosic biomass feedstocks, waste fat/ oil/ greases)
Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ – SPK)	50%	Cellulosic or starchy feedstocks
Catalytic Hydrothermolysis Synthesized Kerosene (CH – SK)	50%	Fatty acids/ fatty acid esters/ lipids from waste fats/ oils / greases
Hydrocarbon – Hydroprocessed Esters and Fatty Acids	10%	Alga oil

According to the International Civil Aviation Organization (ICAO), over 360,000 commercial flights have used SAF at 46 different airports mainly concentrated in the U.S.A and Europe [1]. In 2011 Air France has operated its first flight using SAF [4]. Between 2014 and 2016, Air France has operated 78 flights between Paris – Toulouse and Paris – Nice, using 10% SAF in the fuel mixture. This long-term test phase confirmed that the use of 10% SAF in the fuel mixture had no impact on the aircrafts, engines, or ground operations. In November 2022, Air France – KLM took an important first step by signing the first supply contracts with Neste and DG Fuels for the delivery of 1.6 million tons of SAF between 2023 and 2036. They have also signed a memorandum of understanding with Total Energies for the delivery of 800,000 tons of SAF between 2023 and 2030. By 2030 Air France aims to incorporate in the fuel mixture at least 10% SAF on all its flights, and by 2050 to incorporate in the fuel mixture 70% SAF on all its flights [4]. United Airlines was the first U.S. airline to test SAF in 2009 [5]. Their first passenger flight using 100% SAF in one engine took place in 2021. Airbus, Rolls-Royce, the German Aerospace Center (DLR) and SAF producer Neste collaborated in Emission and Climate Impact of Alternative Fuels (ECLIF) project in which the impact of flying on 100% SAF has been measured on a real flight in 2021 [6]. An Airbus A350 commercial aircraft powered by two Rolls-Royce Trent engines has been used. Compared to a reference Jet A fuel, the number of contrail ice crystals per mass of unblended SAF consumed was reduced by 56%, which could significantly reduce the climate-warming effect of contrails. These results show that using SAF in flight could

significantly reduce the climate impact of aviation in the short term by reducing non-CO₂ effects such as contrails, in addition to reducing CO₂ emissions over the lifecycle of SAF. In 2022, Airbus has performed another flight using a A380 aircraft powered by 100% SAF [7]. The used SAF, provided by TotalEnergies, was made from Hydroprocessed Esters and Fatty Acids (HEFA), free of aromatics and sulphur, and primarily consisting of used cooking oil, as well as other waste fats. Currently all Airbus aircrafts are certified to fly with up to a 50% blend of SAF mixed with kerosene. The aim is to achieve certification of 100% SAF by 2030 [7,8]. To demonstrate the versatility of SAF, Airbus and Neste also collaborated on Australia's first helicopter flight using SAF. A demonstration flight on an Airbus H130 helicopter using blended SAF was performed in early 2023 during the Avalon Airshow [8]. These developments show that SAF has become an important practical option for reducing the climate impact of aviation, both through life-cycle CO₂ reduction and through the mitigation of other non-CO₂ effects.

The majority of current research studies focus on the production, sustainability, and economic feasibility of SAF, with less emphasis on combustion characteristics and emissions compared to standard Jet A, and their blends. Also, due to issues such as airworthiness safety and adaptability, existing research has mostly focused on the emission performance of SAF when blended with traditional fuels at concentrations lower than 50%, leaving the emissions characteristics of higher blending ratios to be explored.

The research work conducted by Alsulami et al. [9] involved investigating the combustion characteristics of five different oxygenated biofuels (ethanol, acetone, butyl butyrate, iso-pentanol, and butanol) blended with Jet A, to examine how variation in the physical and chemical properties of biofuels can altered the combustion performance. Two biofuels blending ratios of 20% and 50% by volume have been considered. The investigation focused on the flame appearance, flame stability, emissions, and the corresponding gas temperature at two lean conditions. The impact of alcohol - Jet A blends on the performance and emissions of aviation micro-turbojet engines has been examined by Cican et al. [10]. Propanol, butanol, pentanol, hexanol, heptanol, and octanol were tested at 10%, 20%, 30% concentrations and mixed with Jet A, to fuel a JetCat P80 micro-turbojet. Butanol and octanol emerged as viable alternatives, balancing emissions reduction and efficiency. Silvestru et al. [11] have investigated how octanol, used as a renewable additive in Jet A fuel, influences the performance and emissions of aviation micro-turbo engines. Blends containing 10%, 20%, and 30% octanol, with an additional 5% n-heptane, were tested to closely replicate Jet A's physical-chemical properties. The combustion tests results support octanol as a viable sustainable additive, offering substantial emission benefits with only minor efficiency trade-offs. The particulate matter emission reduction characteristics of small turbofan engines fuelled with 100% HEFA – SAF have been experimentally evaluated and compared with traditional fuels by XU et al. [12]. A review of the research conducted between 2017 – 2025 in the field of sustainable aviation fuels is presented in [13]. Studies show that 100% SAFs are cleaner and pose fewer health risks than fossil Jet A. However, no ASTM certification is available for 100% drop-in SAF for commercial aviation. The conclusion of the review is that future research should investigate how SAF blends with more than 50% SAF mixed with Jet A burn and the emissions produced, and explore newer sources for SAF. An emissions comparison of 100% SAF with bio-aromatics and conventional jet fuel has been carried out by Jarin et al. [14]. The experimental test campaign was carried on an engine based on a MAKILA 2B turboshaft in a test cell of SafranTech. The tests did not identify any performance differences between the two fuels, including turbine reactivity and equipment degradation. While NO emissions were found equivalent, significant reduction in CO and soot were measured.

In this context, the present article reports the results of preliminary SAF/kerosene blends combustion tests carried out within the Horizon 2020 project Holistic Green Airport (OLGA). Combustion tests have been performed in COMOTI's Combustion Chamber Laboratory on a fire tube that equips a micro gas turbine used as an APU (Auxiliary Power Unit). Given the aviation industry goal of flying with 100% SAF, different SAF/kerosene blends have been tested, with SAF percentage ranging from 15% to 100%. The used SAF has been purchased from TotalEnergies and it has been obtained using the HEFA pathway. During all tested regimes the following functioning parameters have been monitored: air flow (m³/h), air pressure at combustion chamber inlet (bar), fuel flow (l/min), fuel pressure (bar), exhaust gas temperature (°C). The NO_x, CO, CO₂ and O₂ concentrations in the exhaust gas have been monitored using a gas analyser. The blow-off limit has been determined for each tested fuel. The interior of the fire tube has been inspected visually before and after the combustion tests to identify possible deposits formation.

Due to the limitations of the existent infrastructure at the moment when the experiments have been performed, the tests have been carried out at atmospheric pressure. Consequently, the tested operating regimes do not fully reproduce the nominal pressure and air flow rate of the used APU combustor. The present results should therefore be regarded as preliminary comparative data, useful for identifying trends associated with the SAF blending ratio, while more representative tests will be performed in future work using COMOTI's newly commissioned high-pressure air facility. With high-pressure air (up to 25 bar) and

higher air flow rate (up to 10 kg/s) available, the investigation of gas turbine realistic operating conditions will be possible.

The objective of the present work is to experimentally assess the influence of high SAF blending ratios, up to 100% SAF, on fuel consumption and gaseous emissions of a combustor part of a micro gas turbine used as an APU. The novelty of the work lies in the experimental evaluation of SAF/kerosene blends with over 50% SAF, going up to 100% SAF, with emphasis on NO, CO, CO₂, O₂ concentrations in exhaust gas measurement, blow-off behaviour and higher heating value determination. Although the present campaign has been performed under atmospheric pressure conditions, the study provides useful insight into the combustion response of high SAF blends and supports future testing at more representative pressure and load conditions.

2. EXPERIMENTAL SETUP

The experimental campaign has been carried out on one of the existing test lines within COMOTT's Combustion Chamber Laboratory. The testing rig included: a liquid fuel supply system, an air source, a combustion chamber assembly, a butterfly valve located at the combustion chamber outlet, an air compressor for butterfly valve actuation, and exhaust gases chimney. A diagram of the test line is shown in Fig. 1, while the installed combustion chamber assembly is presented in Fig. 2.

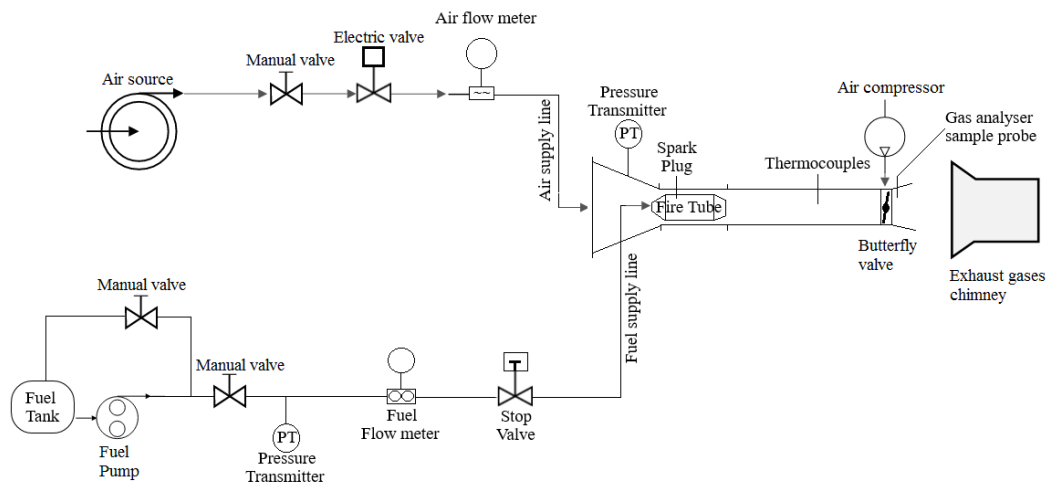


Fig. 1 Test line diagram

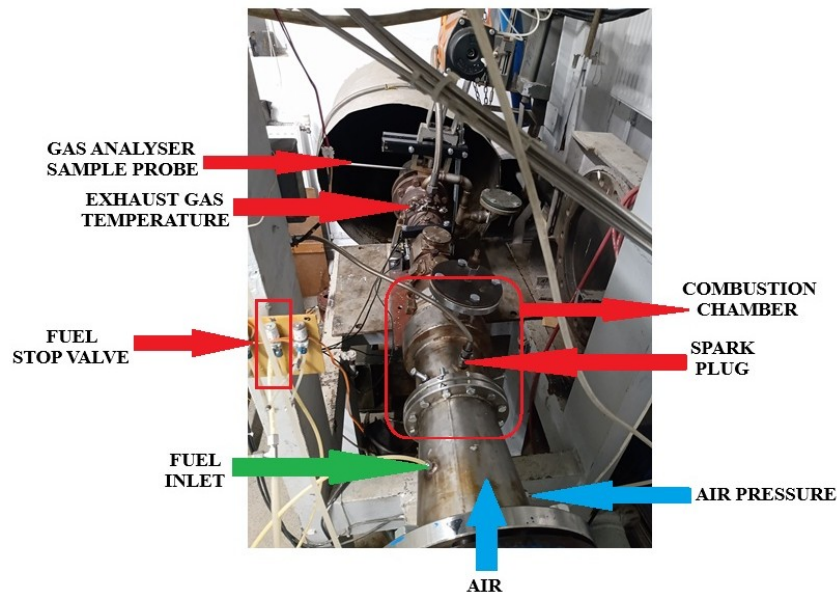


Fig. 2 General view of the experimental test rig

The air necessary for the combustion tests has been delivered by an air-blower. The maximum available air flow was of 825 m³/h (Fig. 3), at atmospheric pressure, as indicated by the ultrasonic flow meter installed on the air supply line. This air flow limitation had a direct influence on the achievable operating conditions during the experimental campaign.



Fig. 3 Air flow meter display

The fuel supply system consisted of: a room-temperature fuel tank, a fuel pump, manual valves both on the delivery and on the bypass pipes, an electrically actuated stop valve placed upstream the injector for safety purposes, a pressure transducer and flowmeter placed on the delivery pipe. This configuration allowed the adjustment and monitoring of the fuel flow supplied to the combustor for each tested operating regime.

The combustion chamber components used in the present study, namely the fire tube, fuel injector, and spark plug come from a Garrett GTP 30-67 micro gas turbine [15], used as an APU (Fig. 4).



Fig. 4 Fire tube interior

The instrumentation used during the experimental campaign is summarised in Table 2.

Table 2. Experimental setup instrumentation

Parameter	Unit	Instrumentation	Position
Air flow	m ³ /h	SICK AG, Waldkirch, Germany - Ultrasonic flow meter [16], 32 – 4500 m ³ /h, max. press. 250 bar, -40°C – 105°C, accuracy ±1%	Air supply line
Air pressure	bar	Honeywell, Charlotte, NC, USA - ST 3000 Pressure Transmitter, 0 – 10 bar, -40°C – 110°C, accuracy ±0.0375%	Combustion chamber inlet
Fuel mass flow	l/min	KEM Koppers Elektromechanik GmbH, Karlsfeld, Germany - ZHM gear flow meter [17], 0.02 – 3 l/min, max. press. 420 bar, -40°C – 180°C, accuracy ±0.1%	Fuel supply line
Fuel pressure	bar	PMA GmbH, Germany - Pressure transmitter, 0 – 10 bar, accuracy	Fuel supply line

		$\pm 0.2\%$	
Flue gases temperature (TF1, TF2, TF3, TF4)	$^{\circ}\text{C}$	Thermocouple type K, $T_{\text{max}} = 1200^{\circ}\text{C}$, accuracy $\pm 1\%$	Combustion chamber outlet
CO / CO ₂ / NO _x / O ₂ concentration	ppm / % / ppm / %	Horiba Ltd., Kyoto, Japan - PG 350 gas analyser [18]	Exhaust gases outlet
Butterfly valve position	% open	Electro-pneumatic positioner, $P_{\text{max}} = 10 \text{ bar}$, $T_{\text{max}} = 80^{\circ}\text{C}$	Exhaust gases outlet

The exhaust gas temperature has been measured using four thermocouples placed at the combustor outlet, allowing the calculation of an average outlet temperature for each tested regime. This average temperature has been later used to define and compare the operating conditions investigated in the present campaign. The gas analyser probe has been installed at the exhaust gas chimney entrance in order to monitor the evolution of the main gaseous species throughout the combustion tests. Although the present setup was not able to reproduce the nominal operating conditions of the used APU combustor, it was adequate for a first comparative investigation of the SAF blending ratio influence on combustor behaviour and exhaust gas emissions.

3. TESTED FUNCTIONING REGIMES

The combustion tests have been performed at atmospheric pressure, with the butterfly valve completely opened. Attempts have been made to increase the operating pressure by adjusting the butterfly valve position. However, due to the limited air flow available during the present campaign, no stable functioning regimes could be maintained. Under these conditions, the objective of the campaign has been to obtain preliminary comparative data for different SAF/kerosene blends under the same achievable stable operating conditions. During the tests, the air flow has been maintained constant at $825 \text{ m}^3/\text{h}$, while varying the fuel flow, aiming to obtain four different temperature values at the combustion chamber exit. Thus, four functioning regimes have been achieved. The fuel flow has been adjusted by varying the output voltage of the electric power supply driving the variable speed gear liquid fuel pump. SAF/kerosene mixtures, in different proportions, have been used as fuel. Table 3 summarizes the tested regimes and fuels. Each functioning regime has been maintained for 3 minutes in order to ensure adequate stabilisation and a proper sampling of the exhaust gas. Using the Combustion Chamber Laboratory Data acquisition and control system, the following parameters have been recorded during each test, at a frequency of 1 Hz: the fuel flow (l/min), the fuel pressure (bar), the air pressure (bar), the exhaust gas temperature ($^{\circ}\text{C}$). The Data acquisition and control system screen during the tests is presented in Figure 5..

Table 3. Tested regimes and fuels

REGIME FUEL	Regime 1 T3 = 800°C	Regime 2 T3 = 700°C	Regime 3 T3 = 500°C	Regime 4 T3 = 400°C
100% kerosene	X	X	X	X
15% SAF / 85% kerosene	X	X	X	X
30% SAF / 70% kerosene	X	X	X	X
50% SAF / 50% kerosene	X	X	X	X
75% SAF / 25% kerosene	X	X	X	X
100% SAF	X	X	X	X

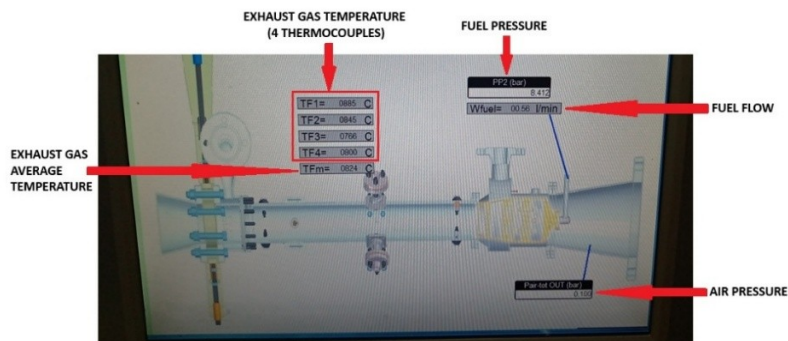


Fig. 5 Data acquisition and control system screen

4. COMBUSTION TESTS RESULTS

Figures 6 – 9 present the averaged values of the functioning parameters recorded during the tests.

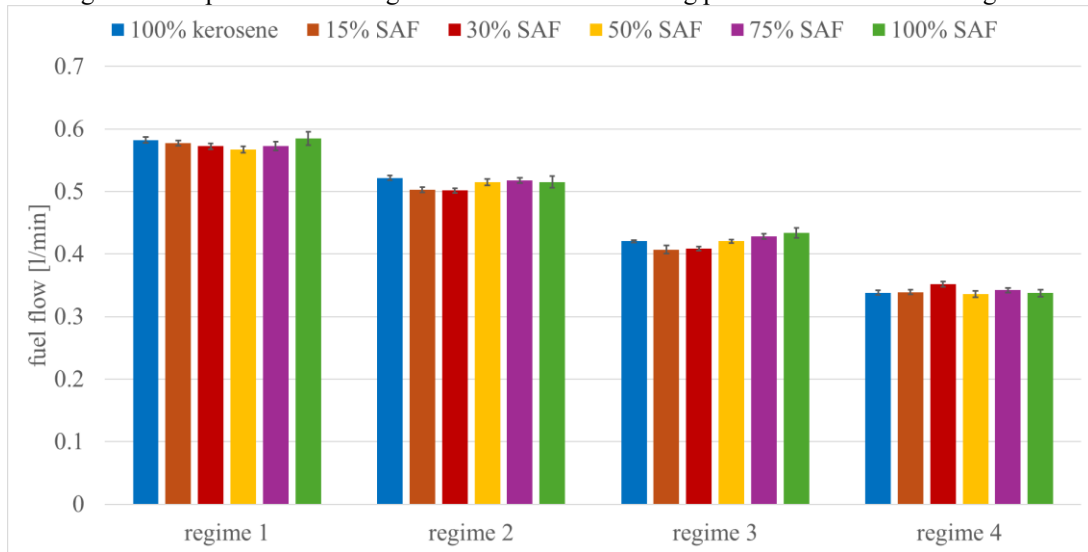


Fig. 6 Fuel flow

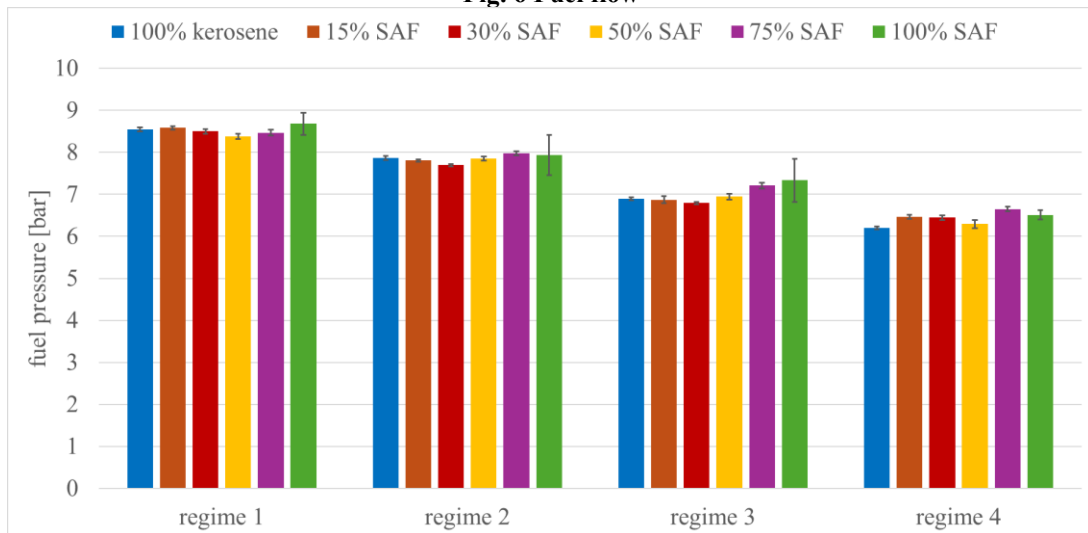


Fig. 7 Fuel pressure

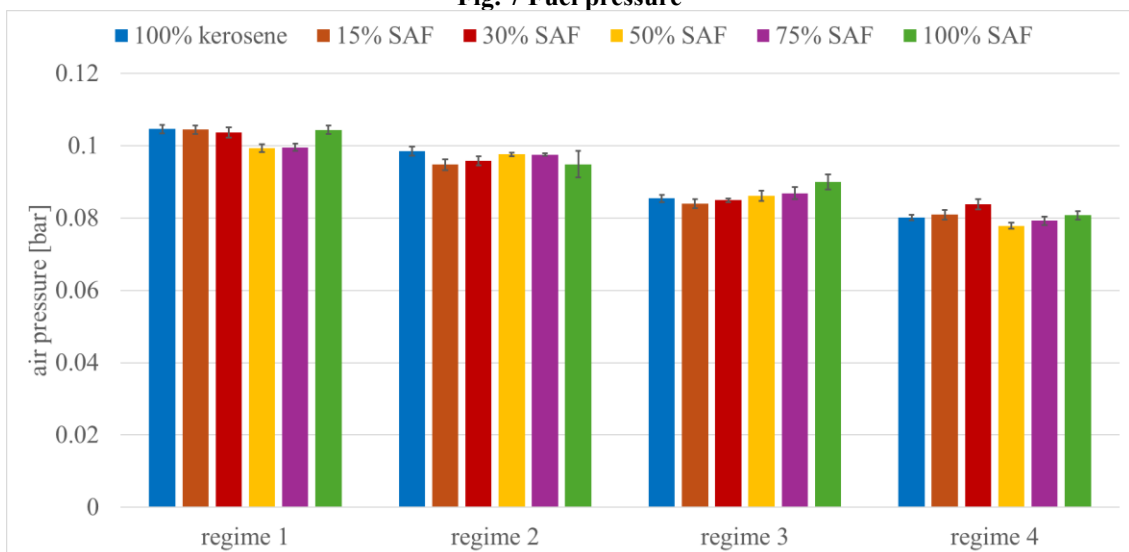


Fig. 8 Air pressure

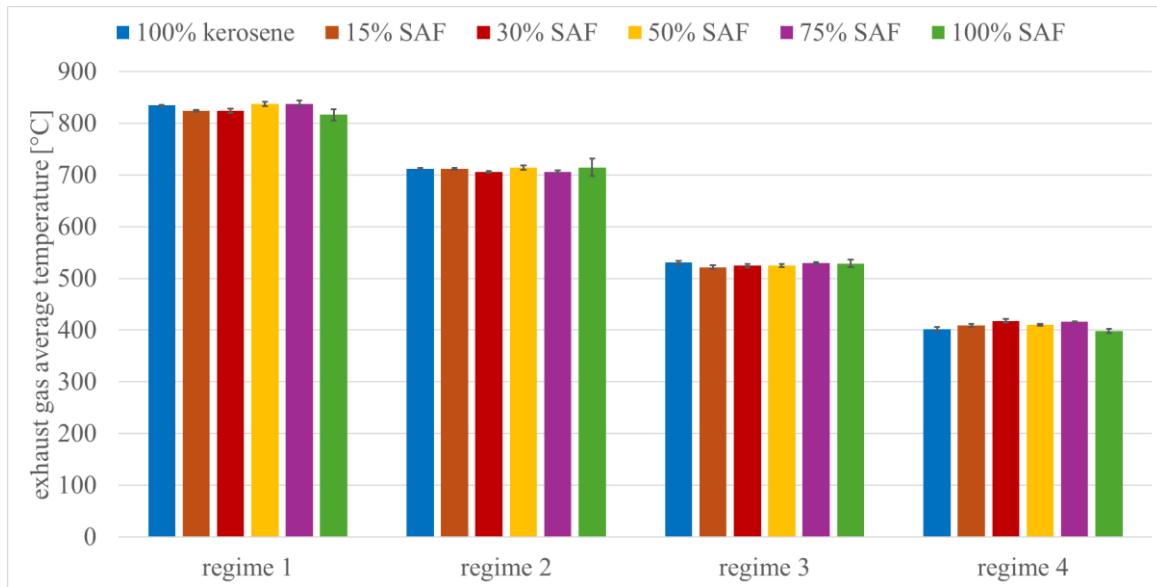


Fig. 9 Exhaust gas average temperature

As mentioned in section 3, four functioning regimes have been tested. The measured temperatures shown in Figure 9 confirm that the selected regimes correspond to average exhaust gas temperatures of 800°C, 700°C, 500°C, and respectively 400°C. The differences between the tested fuel blends are small, indicating that comparable thermal loading conditions have been obtained for all investigated SAF/kerosene mixtures. The fuel flow and exhaust gas temperature are in good correlation. As shown in Figure 6, functioning regimes with lower exhaust gas temperature have been obtained by reducing the fuel flow. The fuel flow goes hand in hand with the fuel pressure. The increase of the fuel flow leads to a rise of the fuel pressure, as it can be seen from Figure 7. The influence of the used fuel upon the fuel flow and fuel pressure is relatively small. This indicates that the combustor was operated in a comparable manner across the full blending range, including 100% SAF. The measured air pressure at the combustion chamber inlet, shown in Figure 8, also exhibits small variations between the tested fuels. The rise of the flue flow leads to a slight increase of the air pressure. This can be explained by a rise of the pressure inside the fire tube as the combustion temperature increases due to a larger fuel flow, while the air flow remains constant.

Figures 10 – 13 present the averaged exhaust gas concentrations of NO [ppm], CO [ppm], CO₂ [vol. %], respectively the O₂ [vol. %], for all tested fuel blends and functioning regimes. The presented values are averaged over the 3 minutes in order to ensure adequate stabilisation and a proper sampling of the exhaust gas.

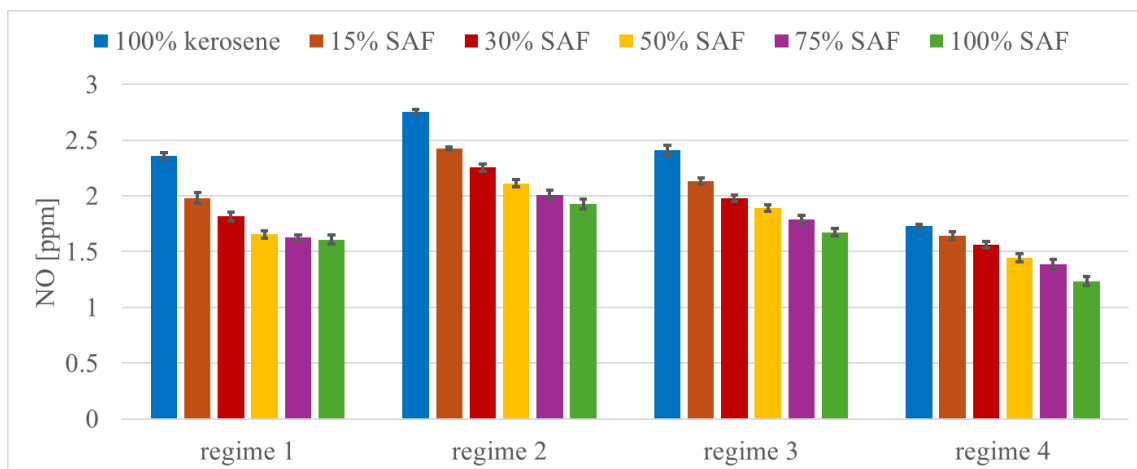


Fig. 10 NO concentration

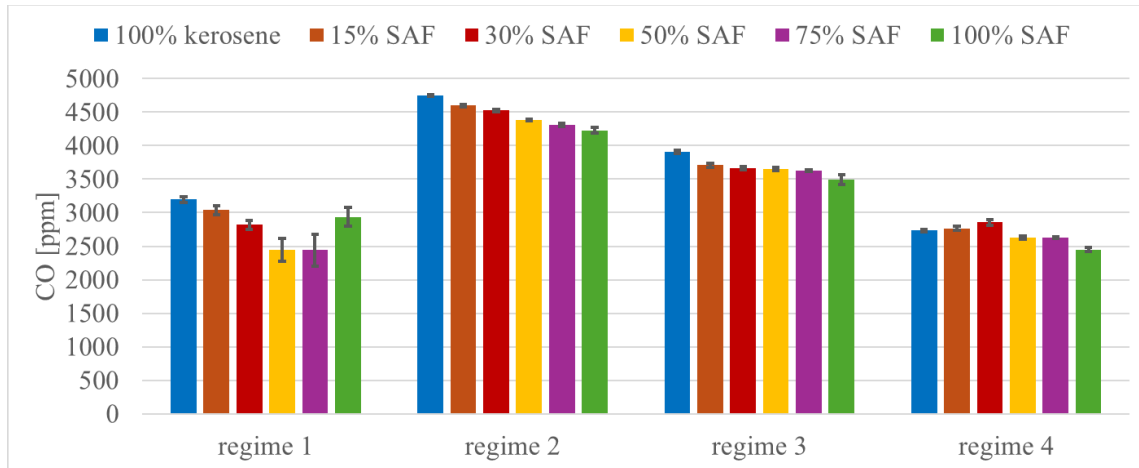


Fig. 11 CO concentration

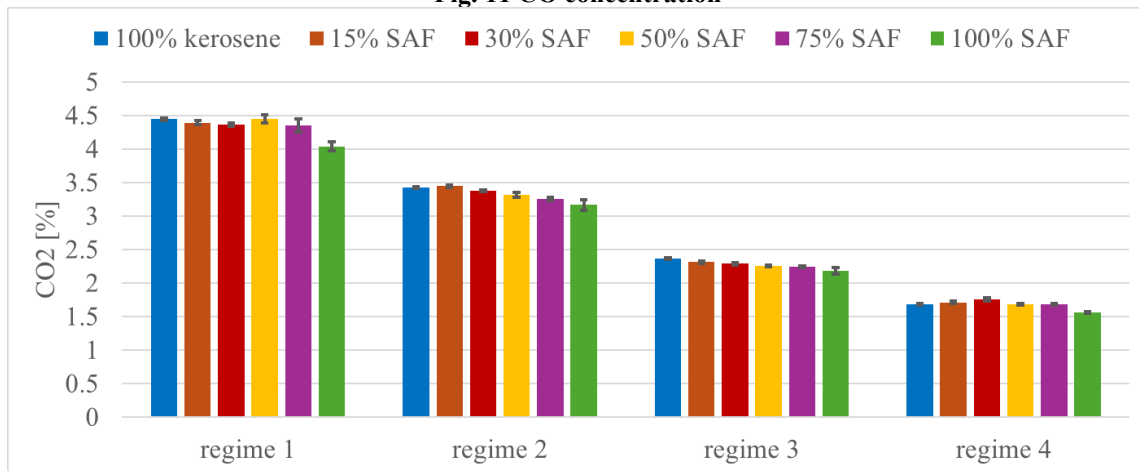
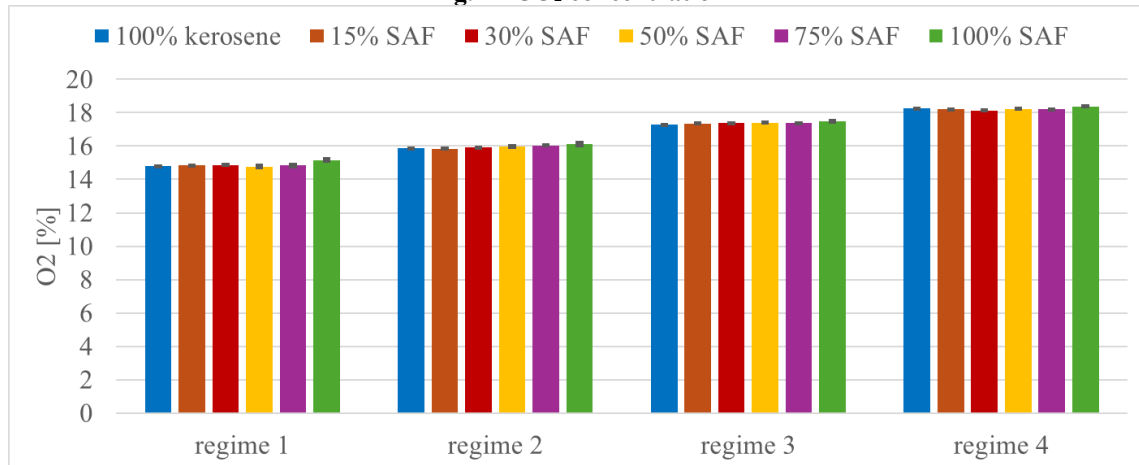
Fig. 12 CO₂ concentrationFig. 13 O₂ concentration

Figure 10 shows a significant decrease in NO concentration in the exhaust gas can as the percentage of SAF in the fuel mixture increases, during all 4 functioning regimes tested. This can be explained by the decrease in the aromatic compounds level in the fuel mixture due to the increase of the SAF percentage. Aromatics are fuel compounds that during the combustion process are oxidized leading to the formation of NO. Based on the fuel certificates, the SAF used during the combustion tests has a low content of aromatics, below 2%, while kerosene has a content of 17%. Differences in fuel composition can affect local flame structure, heat-release distribution and peak temperature zones, which in turn influence NO formation. The trend followed by the NO concentration is in accordance with the behaviour of the exhaust gas temperature, the NO concentration increasing with the growth of the temperature. The growth of the exhaust gas

temperature favours the dissociation of the nitrogen molecules which leads to the formation of nitrogen oxides.

As regarding the CO and CO₂ concentrations in the exhaust gas, the differences between the used fuels are very small, regardless of the tested regime, as it can be seen from Fig. 11, respectively Fig. 12. This was to be expected, SAF being a hydrocarbon in the C11 – C16 class, just like kerosene. The slightly higher CO emissions as the percentage of SAF in the fuel mixture decreased, can be explained by the higher aromatics content of Jet A. Aromatics have a higher carbon concentration. This favours the formation of more CO during combustion.

The variation of the O₂ concentration in the exhaust gas, presented in Figure 13, is consistent with the thermal load of the tested regime. Higher O₂ levels are measured at lower temperature regimes, while lower O₂ values are associated with the higher temperature operating points. This behaviour reflects the lower fuel flow rates required for the low temperature regimes and the corresponding changes in the global fuel-air balance.

Keeping the air flow constant at 825 m³/h and gradually reducing the fuel flow, the blow-off limit has been determined for each tested fuel. Although the differences are modest, the results presented in Table 4 indicate that higher SAF percentage in the fuel mixture positively influences combustion stability under the investigated conditions. Given that the blow-off tests have been performed at atmospheric pressure and constant air flow, the presented values should not be directly extrapolated to real engine operating conditions. Even so, the results remain relevant from a comparative standpoint. They show that operating with high SAF content fuels, including neat SAF, is feasible.

Table 4. Blow-off limit

Fuel	Fuel pressure (bar)	Fuel flow (l/min)	Exhaust gas average temperature (°C)
100% kerosene	3.8	0.21	235.0
15% SAF / 85% kerosene	3.7	0.21	228.7
30% SAF / 70% kerosene	3.8	0.21	217.8
50% SAF / 50% kerosene	3.7	0.20	216.8
75% SAF / 25% kerosene	3.9	0.21	214.3
100% SAF	3.8	0.20	210.2

The interior of the fire tube has been inspected visually before (Fig. 14) and after (Fig. 15) the combustion tests in order to observe the presence of any deposits on the walls resulting from the combustion process. The observed deposits are most likely related to the off-design nature of the investigated operating points, which were significantly different from the nominal operating regime for which the combustor was originally designed. Another explanation for the soot deposits is the presence of aromatic compounds in the used fuels, especially kerosene. Aromatics, particularly polycyclic aromatic hydrocarbons (PAHs), are known precursors to soot. Increased aromatic content enhances the formation of PAH and soot particles, which often occur in tandem with increased NO formation [19].

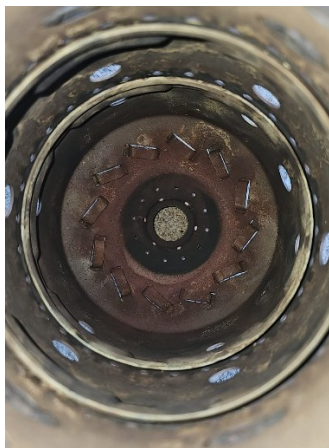


Fig. 14 Fire tube primary zone before testing



Fig. 15 Fire tube primary zone after testing

5. HIGHER HEATING VALUE DETERMINATION

The calorific power / heat of combustion is an important characteristic of a fuel. This represents the total energy released as heat when a fuel undergoes complete combustion, and is typically measured in MJ/kg, kJ/mol or BTU/lb. Values are often expressed as Higher Heating Value (HHV) or Lower Heating Value (LHV). HHV includes also the heat associated with water condensation during combustion.

The HHV of the used fuel mixtures have been determined using a calorimetric bomb. The equipment's heat capacity was calibrated using a standard substance, namely benzoic acid, thus defining how much heat causes a 1°C temperature rise. The tested fuel samples have been weighted and put into a crucible. The crucible has been placed inside a "calorimetric bomb", namely a sealed metal cylinder which has been pressurized using oxygen. The sealed cylinder has been inserted in a dedicated equipment which automatically evaluates the HHV (Fig. 16). The fuel sample inside the calorimetric bomb is ignited via a firing wire. The resulting temperature increase of the vessel is measured. The fuel sample HHV is calculated using equation (1):

$$HHV = \frac{W \times \Delta T - q_{\text{ignition}}}{m} \quad (1)$$

where W is the calorimeter heat capacity, ΔT is the temperature rise, q_{ignition} is the heat generated by the firing wire, and m is the mass of the fuel sample.

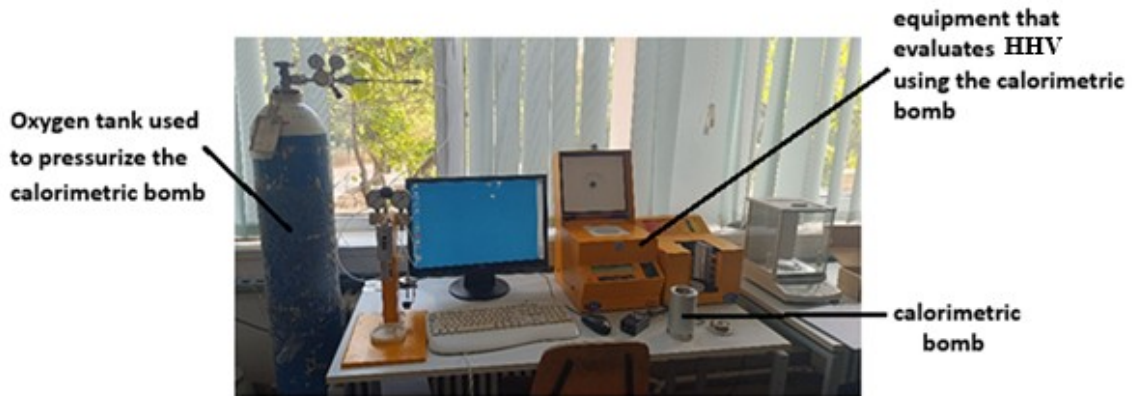


Fig. 16 HHV determination equipment

The results presented in Table 5 show that the increase of the SAF content in the fuel mixture leads to a rise of the HHV. This can be explained by the lower content of aromatic compounds in the fuel mixture with the increase of the SAF percentage in it. Aromatic compounds have a higher specific heat per unit volume, but a lower specific heat per unit mass compared to other hydrocarbons in a fuel. This can lead to a decrease of the fuel's HHV. Aromatic compounds have a higher concentration of carbon and a lower concentration of hydrogen compared to other hydrocarbons. The energy released during combustion comes mainly from the hydrogen content. Thus, kerosene having a higher content of aromatic compounds than SAF has a lower concentration of hydrogen which leads to a lower energy content released during combustion. Although the increase in HHV is moderate, the overall trend is systematic and becomes more pronounced as the SAF percentage approaches 100%.

Table 5. Higher Heating Value of used fuels

Fuel	Higher Heating Value	
	Cal/g	MJ/kg
100% kerosene	10590.9	44.31
15% SAF / 85% kerosene	10594.5	44.32
30% SAF / 70% kerosene	10602.5	44.36
50% SAF / 50% kerosene	10714.2	44.82
75% SAF / 25% kerosene	10736.2	44.92
100% SAF	11002.3	46.03

6. CONCLUSIONS

A preliminary experimental investigation of SAF/kerosene blends combustion has been carried out on a Garrett GTP 30-67 micro gas turbine combustion chamber in order to assess the fuel composition's influence on gaseous emissions, operability, blow-off behaviour and the fuel's higher heating value. Four SAF/kerosene blends have been investigated, with SAF content ranging from 15% to 100%. Four functioning regimes have been tested for each fuel. The regimes have been achieved by varying the fuel flow in order to obtain four average temperature values at the combustion chamber outlet, while keeping the air flow constant. Due to the limitations of the available laboratory setup, the combustion tests have been carried out at atmospheric pressure. Therefore, the presented measured values should be regarded as preliminary comparative data, suitable for identifying trends associated with the SAF blending ratio. The observed behaviour provides a useful first experimental basis for future investigations under more representative pressure and air flow conditions.

The performed combustion tests have highlighted a significant decrease of the NO concentration in the exhaust gas as the percentage of the SAF in the fuel mixture increased. This represents the most important finding of the present work and indicates that high-SAF content fuels provide a measurable reduction in NO emissions under the tested conditions. By contrast, the differences in CO and CO₂ concentrations between the tested fuels were small, suggesting that the global outlet oxidation behaviour remained broadly similar. Burning SAF creates emissions but these are not fossil-based and do not add additional carbon to the atmosphere, thus reducing carbon emissions over the fuel's life cycle compared to using fossil jet fuel. The HHV of the used fuel mixtures, determined using a calorimetric bomb, show a growing trend with the increase of the SAF percentage. The higher HHV of SAF rich fuel blends is relevant because it influences the amount of fuel required to reach a given thermal operating point. During these preliminary combustion tests no problems in the proper functioning of the used combustion chamber have been observed, even when operating with 100% SAF.

The present campaign was limited to atmospheric pressure operation and constant air flow due to constraints of the available laboratory setup. Therefore, the obtained results provide comparative trend information rather than engine representative performance data. Even so, the experimental campaign demonstrates the technical feasibility of operating the investigated combustor with high-SAF content fuel blends, including 100% SAF. Given the aviation industry goal of flying with 100% SAF, these preliminary results provide a sound basis for future investigations under more realistic pressure and load conditions. Also, a more detailed uncertainty and repeatability analysis will be included in future test campaigns performed under more representative operating conditions.

ACKNOWLEDGEMENT

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A Review of Schlieren and Related Optical Methods for Flow Visualization in Fluid Dynamics

Raluca Andreea ROȘU¹, Emilia Georgiana PRISĂCARIU¹, Oana DUMITRESCU¹

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Corresponding author: emilia.prisacariu@comoti.ro

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ABSTRACT: This review aims to synthesize and compare recent developments in optical flow visualization, focusing primarily on Schlieren-based techniques and their modern extensions. Through analysis of both experimental and computational methods, the article identifies the strengths, limitations, and best-use cases of each approach. Emphasis is placed on evaluating sensitivity, quantitative capabilities, ease of setup, and application scope. By highlighting current trends and research gaps, this work provides a comprehensive foundation for selecting and applying suitable diagnostic tools in high-speed and complex flow studies. The review draws from over twenty peer-reviewed sources and suggests future directions for experimental refinement and system integration

KEYWORDS: *optical methods, schlieren, BOS, visualization methods*

1. INTRODUCTION

The study of fluid motion has long relied on the ability to observe flow phenomena in a non-intrusive manner. In particular, compressible and thermally driven flows present significant experimental challenges, since the key physical variables—density, temperature, and pressure—cannot be measured directly without disturbing the system. Optical methods, by exploiting the dependence of refractive index on density, have therefore become indispensable tools in experimental fluid dynamics, aerothermodynamics, and combustion research.

The origins of flow visualization trace back to the mid-nineteenth century with the pioneering experiments of August Toepler, who introduced the Schlieren method as a means of transforming invisible refractive gradients into visible intensity patterns [1]. Since then, a wide spectrum of optical diagnostics has emerged, ranging from classical interferometry and shadowgraphy to advanced quantitative schlieren and background-oriented techniques. Each of these approaches offers unique strengths and limitations in terms of sensitivity, spatial resolution, cost, and ease of implementation, which have shaped their adoption across different scientific and engineering applications.

Among the earliest methods, optical interferometry established itself as the most precise approach for detecting minute refractive index variations, and has been extensively applied to thermal convection, confined flows, and heat transfer problems [2]. Shadowgraphy, in contrast, provided a more accessible qualitative tool, well suited for detecting strong density gradients such as shocks and flames, making it a staple of supersonic and combustion studies [3]. These classical methods paved the way for the development of Schlieren systems, which balanced quantitative sensitivity with experimental practicality and quickly became the most versatile optical tool in aerodynamics and high-speed flow research [4].

¹ Romanian Research and Development Institute for Gas Turbines COMOTI, Romania

Modern advancements have expanded the reach of these techniques. Color schlieren and rainbow-filter methods enhance visual interpretability, while background-oriented schlieren (BOS) has simplified experimental setups to the point where field-scale studies of atmospheric phenomena are now feasible [5,6]. At the same time, computational resources have enabled the development of synthetic and quantitative schlieren, bridging experimental and numerical approaches by providing direct comparisons with CFD simulations [7]. Furthermore, hybrid diagnostics combining schlieren with velocimetry, infrared imaging, or interferometry are pushing the boundaries of what can be measured simultaneously in complex flows [8].

Despite this progress, the literature remains fragmented, with most studies focusing on individual techniques or narrow application domains. A unified review that traces the historical development of optical flow visualization, compares classical and modern schlieren approaches, and highlights their current capabilities and limitations is therefore timely. Such a synthesis is particularly relevant in aerospace engineering, where high-speed flows, jet interactions, and combustion processes demand reliable, non-intrusive diagnostics.

1.1. Historical background

The origins of optical flow visualization can be traced back to the mid-19th century, when August Toepler introduced the first Schlieren system in 1864. His method, based on the deflection of light rays by refractive index gradients, provided an elegant solution to the challenge of visualizing transparent flows, such as convection, shock waves, and jets, which had previously remained invisible to the naked eye [1]. Toepler's work not only demonstrated the scientific potential of optical diagnostics but also established a framework that would guide experimental fluid mechanics for more than a century.

During the late 19th and early 20th centuries, Schlieren methods gradually gained recognition, particularly in Europe, where they were used in early aerodynamic studies and heat transfer research [2]. As the field of aerodynamics expanded in the early 20th century, shadowgraphy emerged as a complementary tool, especially effective in detecting strong gradients associated with shock waves and flame fronts [3]. Shadowgraphy's simplicity made it accessible to a wider range of laboratories, although its utility remained largely qualitative. The period between the two World Wars marked the consolidation of schlieren and shadowgraph techniques in experimental aerodynamics. Notably, they were employed in supersonic and hypersonic research programs, as well as in studies of boundary layer transition [4]. The increasing availability of high-speed cameras during the mid-20th century further enhanced the capability of these methods, enabling the capture of transient flow phenomena in unprecedented detail [5].

By the 1960s and 1970s, the development of laser sources and coherent optics revolutionized optical diagnostics. Interferometric techniques were refined to provide quantitative measurements of density and temperature fields, while holography opened the possibility of time-resolved three-dimensional reconstructions [6,7]. These advances highlighted a growing divide between methods prioritizing quantitative precision (interferometry) and those optimized for qualitative clarity and accessibility (Schlieren and shadowgraphy).

Comprehensive accounts of this historical trajectory are given in the reviews and monographs of the late 20th century, particularly the seminal work by Settles, which synthesized classical developments and modern innovations [8]. More recent historical analyses emphasize how the evolution of Schlieren and related methods reflects broader trends in experimental fluid mechanics: the integration of optical diagnostics with computational tools, the drive toward quantitative accuracy, and the expansion of applications from laboratory-scale experiments to large-scale outdoor studies [9,10].

Thus, the history of Schlieren and related visualization methods is not merely a sequence of technical improvements, but rather a reflection of the changing priorities of fluid mechanics as a discipline: from discovery and qualitative description to precision measurement and predictive validation.

Early techniques such as interferometry and shadowgraphy laid the foundation for refractive index-based visualization. While interferometry provided unmatched quantitative fidelity, its complexity and sensitivity to environmental disturbances restricted its broader use. Shadowgraphy, by contrast, proved robust and simple, making it a method of choice for explosive and field environments.

The introduction of classical Schlieren imaging marked a breakthrough. The simplicity of Toepler's knife-edge setup, combined with the growing availability of mirrors and high-quality optics in the 20th century, made Schlieren the standard tool for visualizing compressible flows. Its capacity to capture shock waves, boundary layers, jets, and thermal plumes positioned it as an indispensable diagnostic, widely adopted in both educational and high-level research laboratories.

1.2. Early Optical Methods: Interferometry and Shadowgraphy

Among the earliest optical techniques for flow visualization, interferometry and shadowgraphy played complementary roles in advancing experimental fluid mechanics.

Interferometry distinguishes itself by its ability to provide quantitative measurements of refractive index variations. Classical configurations such as the Mach–Zehnder interferometer allowed researchers to capture phase differences caused by density or temperature gradients, translating them into fringe patterns that could be analyzed with high precision [11]. Holographic interferometry extended this principle to transient phenomena, enabling the study of rapidly changing fields such as thermal plumes and confined convective flows [12]. Applications included detailed mapping of temperature distributions in heat exchangers, as well as density fields in supersonic test sections [13]. Despite this sensitivity, interferometric systems are highly sensitive to mechanical vibrations and require precise optical alignment, which has limited their widespread adoption in large-scale aerodynamic facilities.

In contrast, shadowgraphy offered a simpler and more robust approach. Instead of detecting phase changes, shadowgraphy visualizes the second derivative of refractive index, making it particularly effective in capturing strong gradients such as shock waves, flame fronts, or cavitation boundaries [14]. This technique became indispensable in supersonic wind tunnels and combustion chambers, where complex shock structures and turbulent mixing could be observed without requiring delicate optical alignment. Advances in high-speed photography further expanded its capabilities, allowing transient features such as shock oscillations and flame instabilities to be recorded at microsecond resolution [15].

Recent developments have even pushed shadowgraphy toward semi-quantitative analysis. By tracking the motion of refractive features in time-resolved images, researchers have extracted approximate velocity fields and shock propagation speeds [16]. Comparative studies have shown that while shadowgraphy lacks the absolute accuracy of interferometry, its robustness and ease of use make it particularly valuable in explosive environments, outdoor testing, and high-Mach number flows [17].

Together, interferometry and shadowgraphy provided the essential stepping stones for the rise of Schlieren methods. While interferometry prioritized precision and quantitative accuracy, shadowgraphy offered accessibility and resilience, even at the cost of reduced sensitivity. Their complementary strengths shaped the methodological landscape of early optical flow diagnostics and highlighted the trade-offs that continue to define the field today.

2. SCHLIEREN TECHNIQUES

2.1. Classical schlieren techniques

Schlieren imaging, pioneered by August Toepler in the 19th century (Figure 1), quickly became one of the most widely adopted optical techniques for flow visualization. Unlike interferometry or shadowgraphy, Schlieren systems directly translate first-order refractive index gradients into visible intensity variations. This capability allowed researchers to capture fine details of fluid structures, from weak thermal plumes to shock waves in high-speed flows [18].

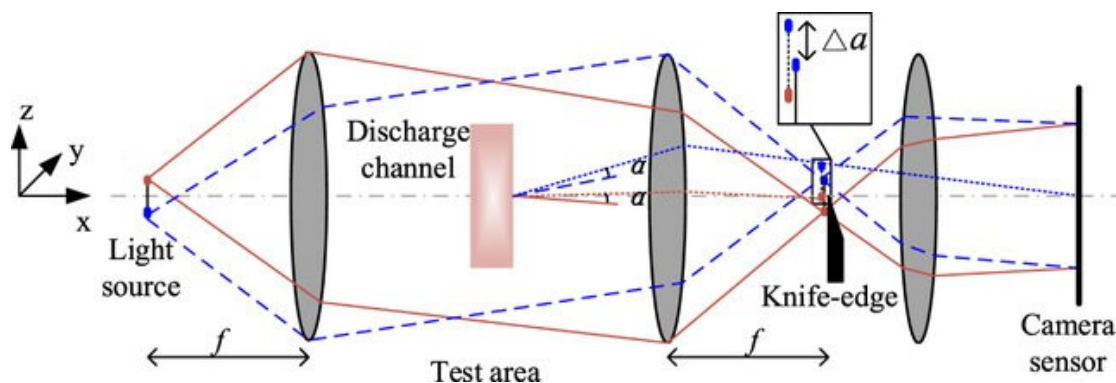


Figure 1. Diagram of Toepler's schlieren system [19]

The classical arrangement consists of a point light source, collimating optics, a knife-edge positioned at the focal point, and a recording device. The knife-edge selectively blocks deflected rays, transforming subtle refractive index gradients into high-contrast images [20]. This relatively simple optical arrangement made the technique accessible to a wide range of laboratories and wind tunnel facilities throughout the 20th century.

Early applications demonstrated its effectiveness in studying supersonic jets and shock-boundary interactions, where schlieren provided unmatched clarity compared to shadowgraphy. For instance, detailed recordings of underexpanded jet structures revealed the presence of Mach disks, barrel shocks, and shock-cell interactions [21]. With the advent of high-speed cameras, schlieren evolved into a dynamic tool, capturing transient events such as unsteady shock oscillations, jet screech tones, and flame instabilities in real time [22].

One of the enduring strengths of classical schlieren lies in its versatility. It has been employed across a spectrum of flow conditions, from low-Mach natural convection to hypersonic shock interactions, demonstrating consistent sensitivity to both weak and strong gradients. Comparative studies have shown that while interferometry provides higher quantitative accuracy, schlieren strikes a balance between qualitative clarity and experimental robustness [23].

Even in its monochromatic form, the method enabled important discoveries in aerospace engineering, including the visualization of transonic flows around airfoils and the study of compressibility effects in boundary layers [24]. These early achievements laid the foundation for later refinements such as color schlieren, background-oriented Schlieren, and quantitative variants, but the classical knife-edge configuration remains a cornerstone of flow visualization.

2.2. Color and Rainbow Schlieren Techniques

While the classical knife-edge configuration provides excellent contrast for sharp density gradients, it lacks the ability to convey directional information. To overcome this limitation, color and rainbow schlieren methods (Figure 2) were developed by replacing the knife-edge with multi-colored cutoff filters. These optical modifications map the magnitude and direction of refractive index gradients into distinct hues, enhancing both visual interpretation and qualitative analysis [25].

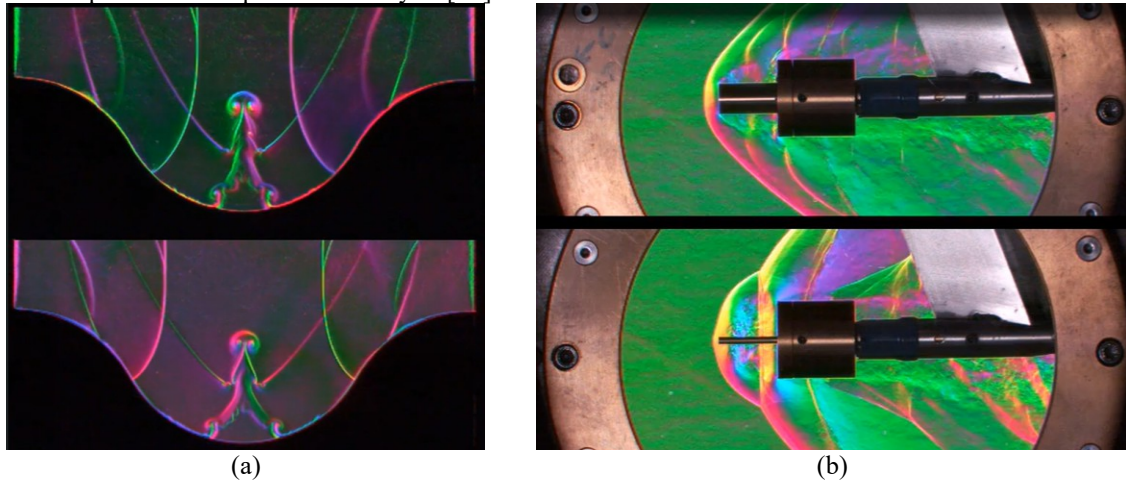


Figure 2. Examples of color schlieren applications: (a) Interaction between pane shockwave and compound reflector (curved inlet and reflector at Mach 1.2 (top) and Mach 1.3 (bottom)), (b) direction-indicating color schlieren – flow instability around blunt body with aerospike [Credits: H. Kleine, UNSW, Canberra, Australia]. [26]

Rainbow schlieren proved particularly effective in bidirectional gradient flows, where traditional knife-edge systems might obscure features due to cutoff orientation. For example, studies of heated jets and natural convection plumes demonstrated how color encoding reveals both upward and lateral gradient components, producing more intuitive images [27]. Beyond visualization, researchers have also leveraged rainbow Schlieren for semi-quantitative analysis, correlating color intensity with deflection angles after careful calibration [28].

The method's appeal lies in its clarity. For combustion studies, rainbow schlieren captured flame fronts and fuel–air mixing zones with greater interpretability than monochromatic setups. Likewise, in supersonic jets, color schlieren allowed shock–shock interactions and expansion fans to be separated more easily based on hue differences [29]. Such improvements made the technique attractive for both laboratory research and educational demonstrations, where qualitative understanding is equally important.

Nevertheless, rainbow schlieren introduces new challenges. Chromatic dispersion and filter imperfections reduce spatial accuracy compared to knife-edge schlieren. Calibration is often complex, requiring mapping of hue to known deflection angles or density gradients. A recent study highlighted the trade-off between filter size and sensitivity: larger filters improved gradient detection but introduced errors in repeatability and quantification [30].

Modern advancements have combined rainbow schlieren with digital post-processing and CFD validation. Synthetic schlieren images lie the ones exemplified in Figure 3, generated from computational simulations can be directly compared to experimental rainbow schlieren fields, creating a powerful framework for verifying numerical models [29]. This synergy between experiment and computation reflects a growing trend in flow diagnostics: integrating optical methods not only as qualitative tools but as benchmarks for predictive simulations.

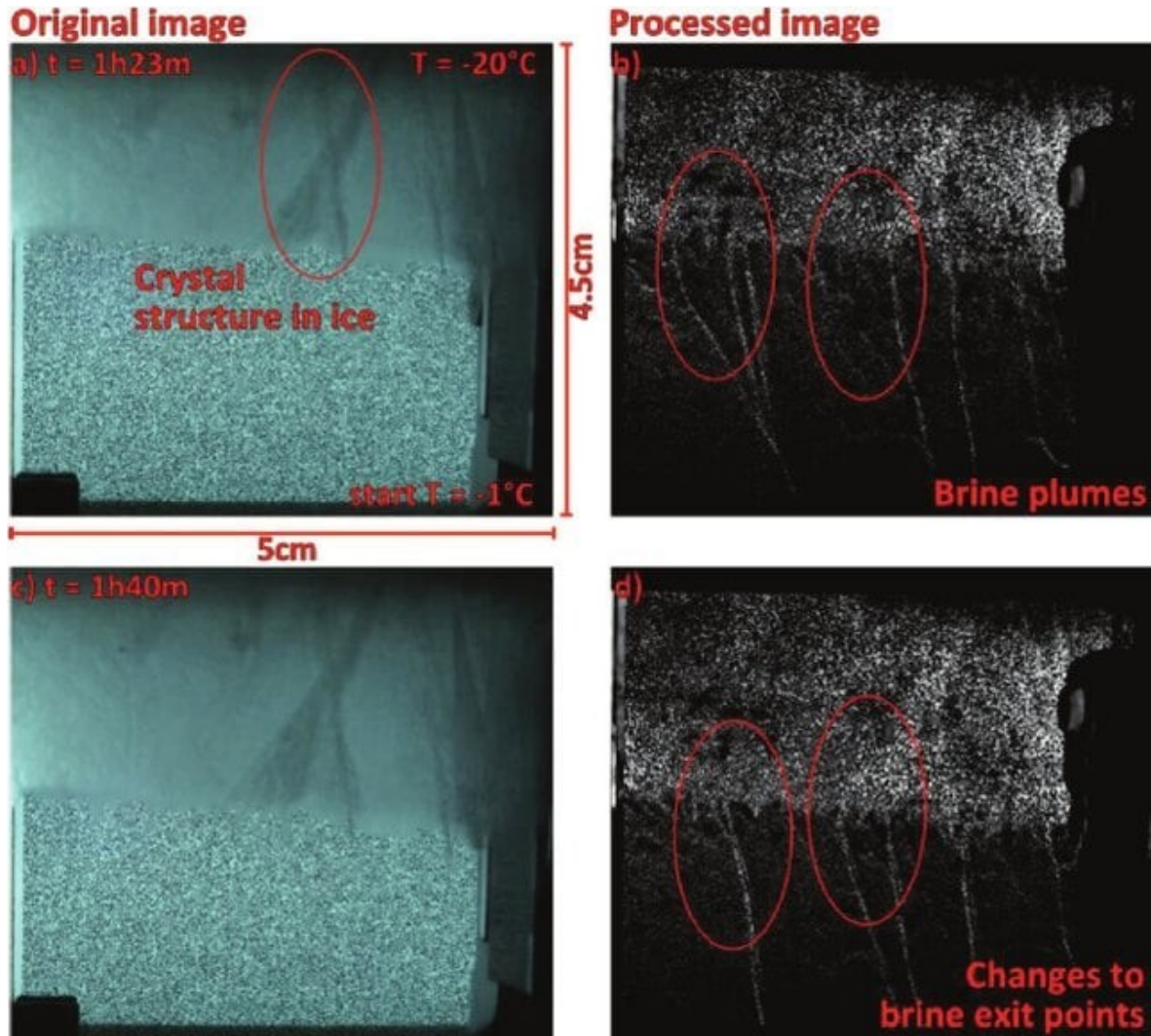


Figure 1. Original (a, c) and processed (b, d) synthetic schlieren images illustrate ice formation from a 35 ppt NaCl aqueous solution. The temperature at the top of the cell was maintained at -20°C , while the ambient room temperature was -1°C . The upper images correspond to 1 hour and 23 minutes after the onset of ice growth, and the lower images to 1 hour and 40 minutes. Over time, the ice layer increases in thickness, with continued development of the crystal structure visible in the original images. Additionally, both the number and spatial distribution of brine plumes evolve. The ice structures appear slightly out of focus due to the camera being focused on the pattern plane rather than the ice itself [31].

In summary, rainbow Schlieren broadened the scope of classical visualization. It offered visual clarity, gradient orientation detection, and educational accessibility, albeit with limitations in calibration complexity and quantitative fidelity. Its legacy continues as a bridge between qualitative observation and modern computational validation.

2.3. Background-oriented schlieren (BOS)

The development of Background-Oriented Schlieren (BOS) marked a paradigm shift in flow visualization, introducing a simple, scalable, and flexible technique that removed the need for precision optics, collimated light, and knife-edge filtering. Instead, BOS relies on tracking the apparent displacement of a random or structured background pattern caused by refractive index variations in the flow. By comparing a reference image (without flow) to a disturbed one (with flow), image correlation algorithms extract local displacements that correspond to density gradients [32].

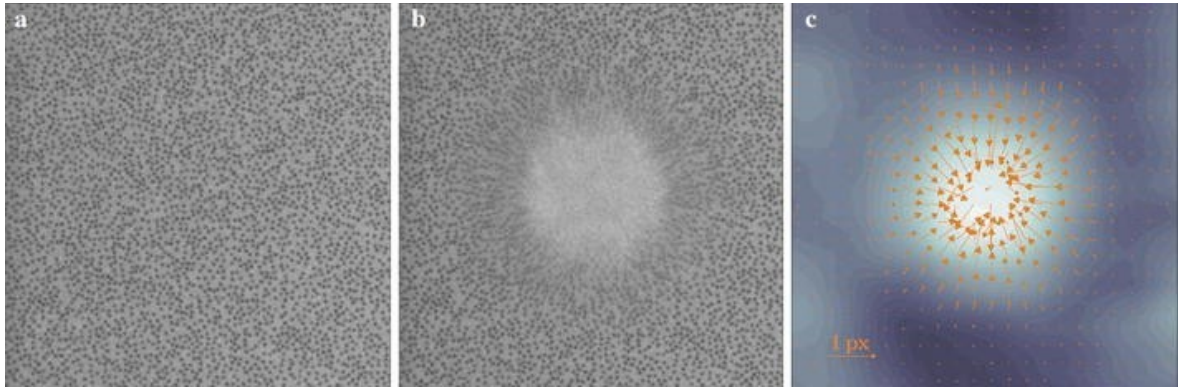


Figure 4. (a) Background pattern prior to, and (b) shortly after, the introduction of a density variation in the flow induced by plasma ignition. (c) Vector field illustrating the displacement correlation between the two recordings, where the grayscale encodes the radial component of the displacement vectors [33].

This digital approach made schlieren diagnostics more accessible and adaptable to environments where traditional systems were impractical. For instance, BOS has been widely applied to large-scale flows, including atmospheric turbulence, shockwaves from explosions, and outdoor aerodynamic testing [34]. Unlike classical schlieren setups constrained by optical benches, BOS can be implemented with only a camera, a patterned background, and image processing software, as exemplified in Figure 5, the result is quantitative.

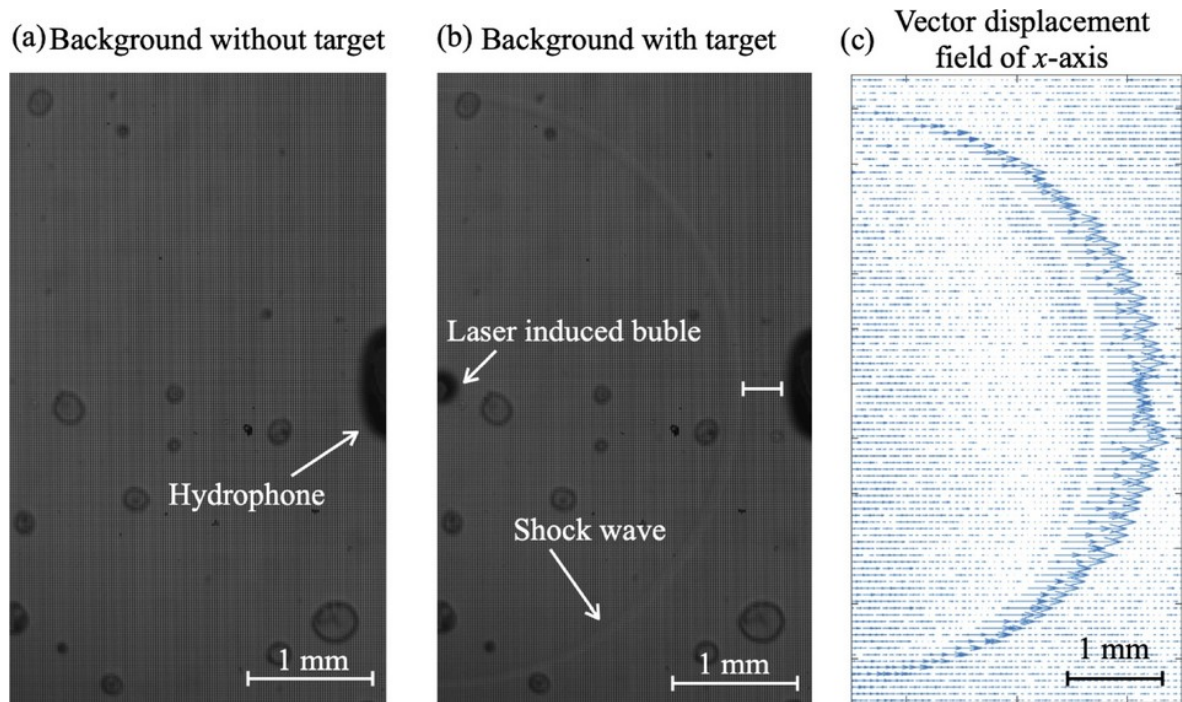


Figure 5. (a) and (b) Background images acquired with and without the target (shock wave), respectively. (c) Vector field of the x-component obtained through displacement detection using the FCD method [35].

A key strength of BOS lies in its scalability. Researchers demonstrated its use in flows ranging from millimeter-scale heat plumes to meter-scale supersonic jets. In aerospace applications, BOS has visualized shock-boundary layer interactions, underexpanded jet structures, and combustion instabilities with remarkable clarity [36]. Its ability to capture transient events with high-speed cameras further extends its utility to explosive environments and safety testing [37].

Nevertheless, BOS faces several limitations. The technique depends heavily on background quality and pattern density: too coarse a background leads to poor resolution, while overly fine structures complicate correlation. Moreover, BOS is sensitive to camera vibration, optical distortions, and misalignment between reference and disturbed images. The result is that while BOS excels in qualitative and semi-quantitative visualization, its absolute accuracy is often lower than calibrated Schlieren or interferometry [38].

Recent advancements have focused on enhancing BOS's quantitative capacity. Methods such as synthetic background calibration, adaptive window correlation, and integration with Particle Image Velocimetry (PIV)

have improved spatial resolution and reduced noise [39]. BOS tomography has also emerged, reconstructing three-dimensional density fields from multiple viewing angles, making it possible to capture volumetric flow structures [40]. This extension is particularly promising in combustion research and high-speed aerodynamics, where full 3D characterization of density gradients is critical.

In summary, BOS represents a modern, digital, and field-ready evolution of schlieren imaging. Its simplicity and scalability have opened new domains—from supersonic aerospace testing to atmospheric optics—where classical methods could not be deployed. While challenges remain in resolution and quantitative fidelity, the integration of BOS with computational tools and tomographic methods positions it as a central technique for the future of experimental fluid mechanics.

2.4. Quantitative schlieren

While traditional schlieren and BOS systems primarily offer qualitative or semi-quantitative insights, quantitative schlieren (QS) techniques were developed to bridge the gap between visualization and measurement. By calibrating the optical system or post-processing image intensities, Schlieren imaging can be transformed into a diagnostic tool capable of delivering density, temperature, and pressure fields.

The fundamental principle is to relate light deflection angles—caused by refractive index gradients—to measurable image intensity variations, as illustrated in Figure 6.

Through calibration, typically involving graded filters, calibration lenses, or photometric references, it becomes possible to derive absolute values of refractive index gradients. Subsequent integration yields density and temperature fields, often with accuracies within 2–3% in controlled laboratory flows [41].

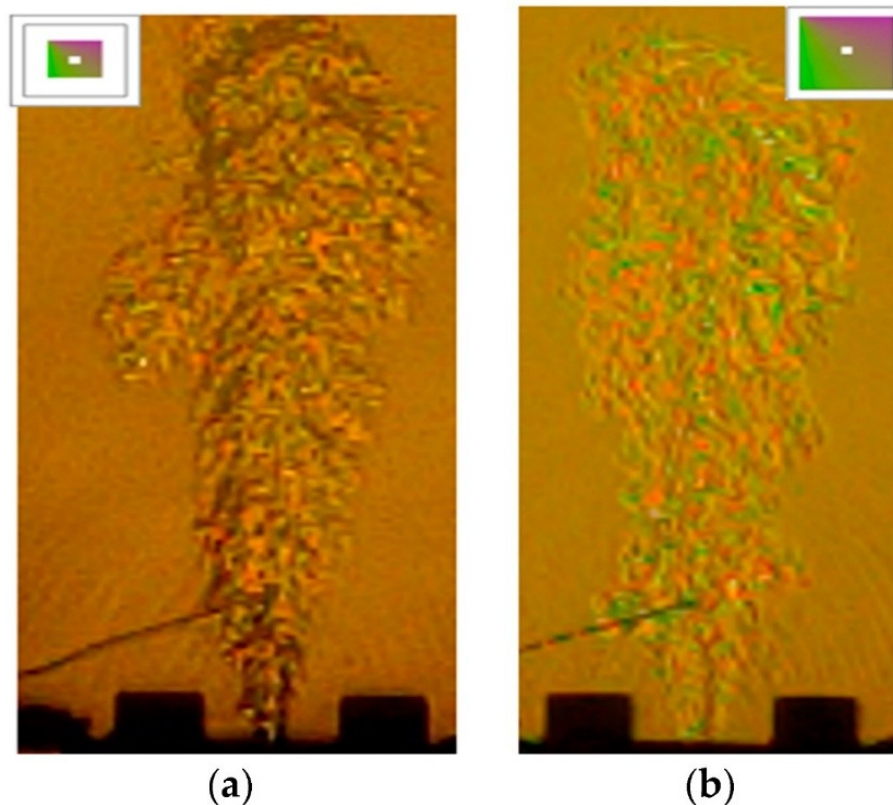


Figure 6. Color filter schlieren using different sized filters identical experimental conditions and phenomenon, hot, round turbulent jet (RTJ), formed by water vapors resulting from a H_2 – O_2 reaction. [42]

One of the earliest approaches to QS involved calibrated knife-edge schlieren, where the knife-edge is replaced by a spatially graded optical filter. By mapping pixel intensity directly to deflection angle, researchers achieved pixel-by-pixel quantitative schlieren imaging [43]. This technique proved particularly effective in laminar boundary layers and natural convection studies, where gradients were sufficiently smooth to allow stable reconstruction. Such an example is presented in Figure 7.

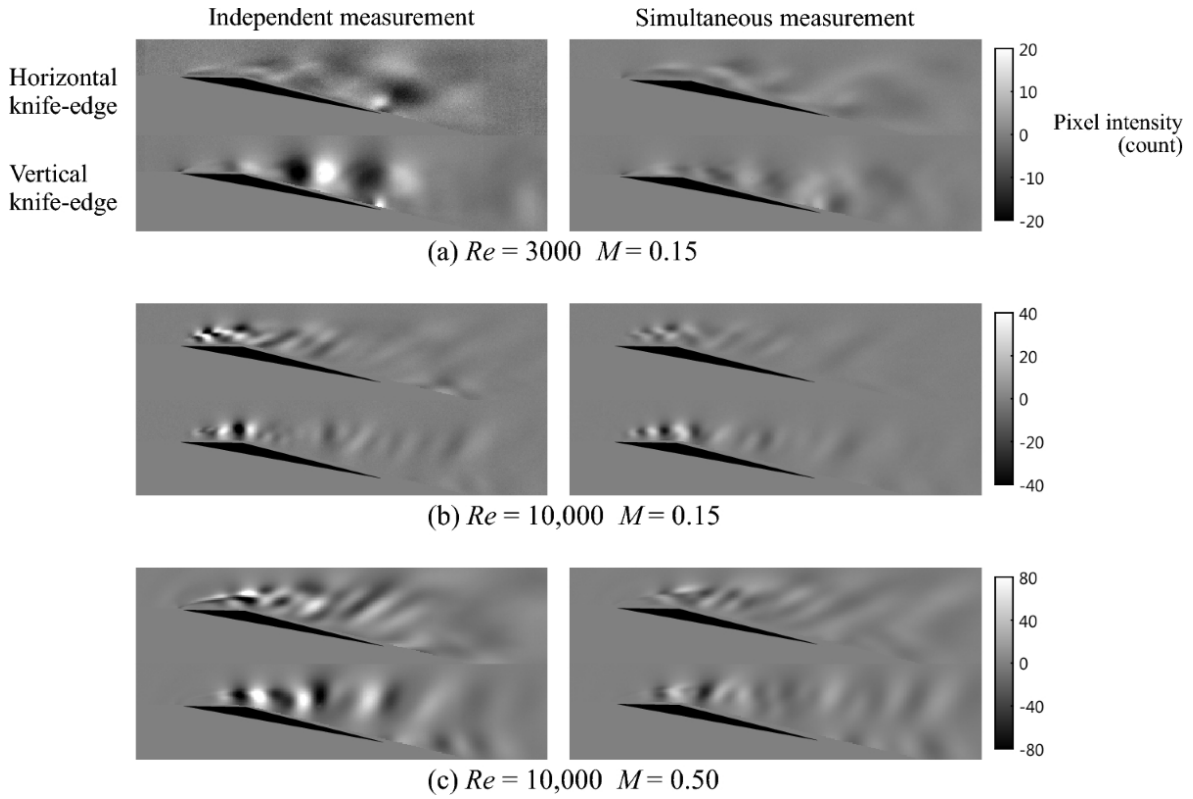


Figure 7. Density field reconstruction from time-series schlieren images via extended phase [44]

Rainbow Schlieren Deflectometry (RSD) represents another important branch of QS. Here, a colored filter substitutes the knife-edge, encoding light deflections into hue variations (as presented in Figure 8). By carefully calibrating the filter and using color-mapping algorithms, one can extract two-component deflection data, enabling reconstruction of both magnitude and direction of density gradients [39]. This capability has been especially valuable in combustion diagnostics, where flame fronts and temperature fields demand two-dimensional resolution.

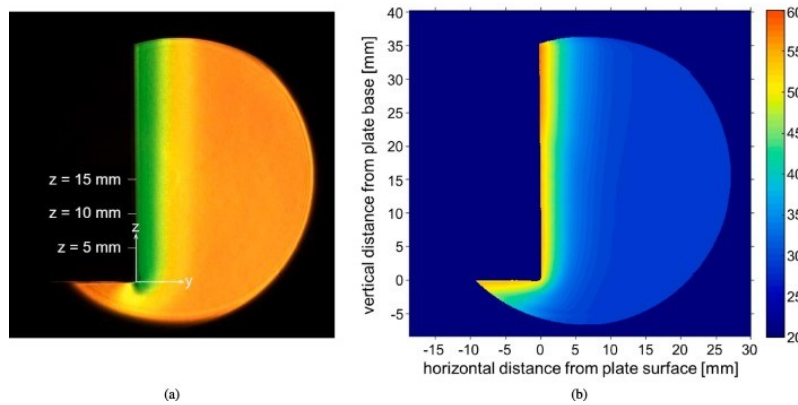


Figure 8 . Experimental results for the temperature field generated by free convection adjacent to an isothermal vertical plate. (a) Rainbow Schlieren raw image with coordinates and scale, using a 1.5 mm one-dimensional filter with vertically oriented hue isolines. (b) Spatial temperature distribution obtained from the raw image in (a) [45].

More recently, hybrid methods combining schlieren with interferometry, BOS, or velocimetry have emerged. For instance, schlieren images can be cross-referenced with Particle Image Velocimetry (PIV) to provide both density and velocity fields in the same test environment [46]. Similarly, combining infrared thermography with calibrated schlieren has allowed simultaneous measurement of temperature distributions and density gradients, critical in supersonic combustion studies [47].

Despite these advances, quantitative schlieren methods face challenges: they require precise calibration, often sensitive to optical misalignments and noise; reconstructions can be ill-posed, especially in turbulent flows with strong three-dimensional gradients; in practice, QS is more suited to planar, steady, or weakly unsteady flows, while highly transient phenomena still rely on qualitative methods.

Nevertheless, the integration of computational Schlieren has begun to alleviate some of these issues. By generating synthetic schlieren images from CFD simulations and comparing them with calibrated experimental results, researchers have developed data assimilation approaches that improve both numerical and experimental fidelity [48].

In summary, quantitative schlieren methods transform a primarily qualitative visualization tool into a rigorous measurement system. Through calibrated filters, color encoding, and hybrid approaches, Schlieren diagnostics now provide reliable access to density, temperature, and stress fields, bridging the gap between fluid dynamics visualization and engineering measurement requirements.

2.5. Advanced schlieren variants (3D, tomography, computational and hybrid imaging)

As flow diagnostics have advanced, so too has the range of schlieren variants, which aim to overcome the inherent limitations of classical 2D imaging. These advanced techniques emphasize three-dimensionality, tomographic reconstruction, and the integration of Schlieren with other diagnostic tools.

One of the most significant innovations is Schlieren tomography, which reconstructs volumetric flow fields from multiple Schlieren views. Instead of providing only line-of-sight integrated data, tomographic Schlieren enables 3D mapping of density gradients by applying algorithms similar to medical CT scans. Using angularly distributed Schlieren images, researchers have reconstructed shock structures and vortex rings in supersonic jets with unprecedented detail [49]. Such methods are particularly valuable in hypersonic aerodynamics, where flow structures are inherently three-dimensional and classical 2D Schlieren is insufficient.

Time-resolved background-oriented schlieren tomography (BOS-T) has also emerged as a powerful approach for capturing unsteady, three-dimensional flows. An example is illustrated in Figure 9. By correlating sequential background distortions across multiple cameras, BOS-T can reconstruct time-dependent density fields, offering a near real-time view of turbulent structures and shock interactions [50]. This technique combines the scalability of BOS with tomographic algorithms, enabling applications from laboratory jets to large-scale atmospheric studies.

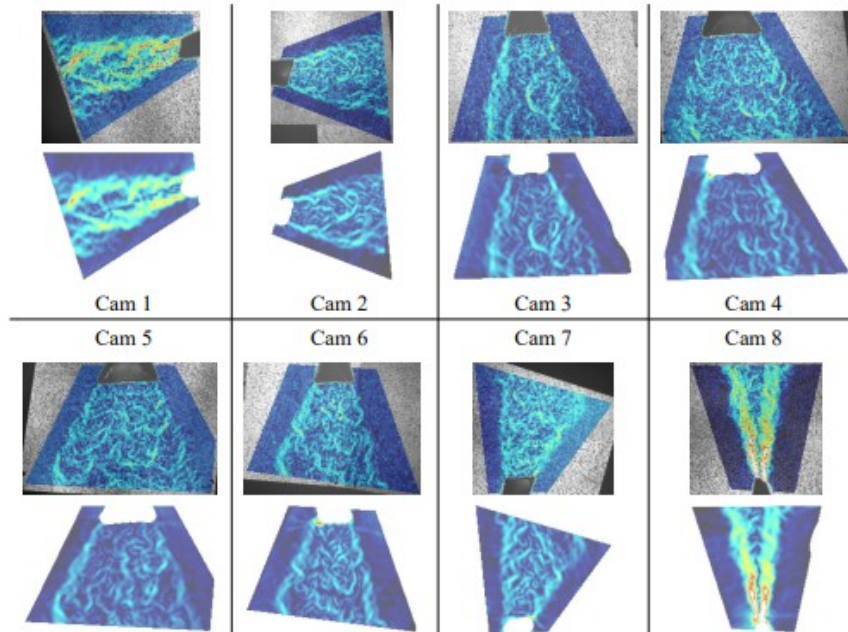


Figure 9. Flat nozzle heat gun 2D BOS results (top image) and back-projection of the reconstruction (bottom image). Contours are colored by total pixel displacement, and have the same scale for all images. [51]

A second major development is computational schlieren imaging, where synthetic schlieren images are generated directly from CFD data and compared with experimental observations. Computational Schlieren serves both as a validation tool for numerical models and as a way to interpret ambiguous flow structures in experimental images. Recent studies have shown that line detection algorithms applied to synthetic Schlieren fields can extract Mach angles, flow direction, and shock positions, allowing quantitative validation of compressible flow simulations [52].

Hybrid imaging techniques further expand schlieren's diagnostic capabilities by integrating it with other optical and acoustic methods. For instance, schlieren combined with laser interferometry can simultaneously deliver qualitative flow visualization and quantitative refractive index measurements [53]. Similarly, coupling

Schlieren with PIV (Particle Image Velocimetry) enables the simultaneous acquisition of velocity and density fields, providing a more complete representation of turbulent mixing in supersonic and transonic flows [54].

High-speed digital imaging has amplified the usefulness of these advanced methods. By operating at several hundred thousand frames per second, schlieren systems now capture transient events such as shock-boundary layer interactions, jet impingement, and detonation waves in unprecedented detail. When combined with computational reconstruction, these datasets serve as both experimental measurements and training sets for machine learning algorithms, pushing Schlieren into the realm of AI-driven diagnostics [55].

In conclusion, advanced schlieren variants are transforming the technique from a 2D qualitative visualization tool into a multi-dimensional, quantitative, and hybrid diagnostic platform. With tomography, computational visualization, and integration with other optical methods, Schlieren continues to evolve, offering the ability to probe flows that were previously beyond reach. The combination of experimental innovation and computational analysis ensures that schlieren imaging will remain a cornerstone of modern flow diagnostics, adaptable to both laboratory and large-scale aerospace environments.

3. APPLICATIONS IN AEROSPACE: JETS, NOZZLES, AND COMPRESSIBLE FLOWS

Among the many fields where Schlieren imaging has proven indispensable, aerospace engineering stands out as one of the most prominent. The visualization of supersonic and hypersonic flows, nozzle exhausts, and shock interactions has been a core application of Schlieren since its earliest adoption in wind tunnel testing. These studies have provided engineers with non-intrusive insights into flow behavior, enabling optimization of nozzle designs, jet mixing efficiency, and aerodynamic stability.

One of the earliest aerospace uses of schlieren was the study of shock wave patterns in convergent-divergent nozzles, where the technique revealed underexpanded jet structures and shock cell formations that were otherwise impossible to measure. Classical knife-edge schlieren, operated with continuous or pulsed light sources, demonstrated how expansion fans and oblique shocks evolve (illustrated example in Figure 10) with varying nozzle pressure ratios [56]. This allowed validation of analytical models for supersonic jet development and noise generation.

High-speed schlieren imaging has further enabled detailed investigation of shock–shock and shock–boundary layer interactions, phenomena critical for the design of hypersonic vehicles and propulsion systems. Experiments using schlieren at frame rates exceeding 100 kHz have captured unsteady shock oscillations and buffet phenomena in scramjet inlets and rocket nozzles, providing insights into stability margins and potential failure mechanisms [57].

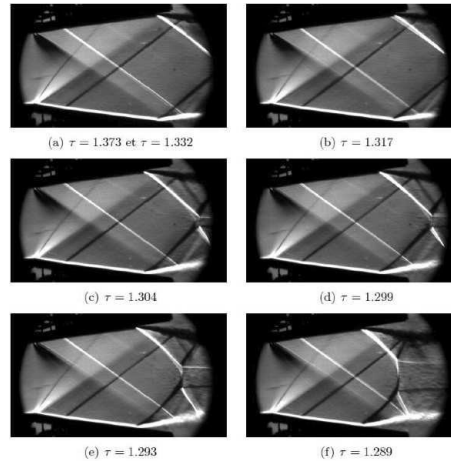


Figure 10. Schlieren flow visualizations for high (left) and low (right) nozzle pressure ratios.[58]

More recent aerospace studies have exploited Schlieren’s ability to analyze multi-stream jet interactions, particularly in the context of noise reduction and mixing enhancement. Time-resolved Schlieren imaging has been combined with Proper Orthogonal Decomposition (POD) to identify dominant flow structures in supersonic rectangular jets, revealing coherent structures responsible for acoustic emissions [59]. These findings have supported the development of advanced jet-noise reduction strategies for next-generation aircraft engines.

Schlieren has also been applied in the context of retropropulsion flows, which are critical for planetary entry and reusable launch systems. Experiments conducted in hypersonic wind tunnels using high-speed Schlieren captured the interaction of retropropulsion jets with oncoming Mach 10 flows, revealing strong shock-induced

separation and unsteady jet flapping [60]. Such visualizations provided essential guidance for designing stable deceleration strategies for Mars landing and reusable booster return.

Beyond propulsion systems, Schlieren imaging has contributed to the aerodynamic analysis of lifting bodies and airfoils in compressible regimes. Inclined and oblique schlieren setups have been used to visualize shock reflections, vortex shedding, and buffet onset around supercritical wings at transonic speeds [61]. These insights have been instrumental in refining computational models and reducing reliance on intrusive probes in wind tunnels.

In summary, schlieren imaging in aerospace has transitioned from a qualitative visualization tool to a diagnostic method integrated with quantitative and computational approaches. From nozzle design and supersonic jets to hypersonic retropropulsion and aerodynamic stability, Schlieren continues to provide critical insight into the complex interactions of shocks, shear layers, and vortices that define high-speed flight.

The enduring appeal of schlieren lies in its cross-disciplinary relevance: aerospace engineering - visualization of underexpanded jets, nozzle design, shock–boundary layer interactions, and hypersonic boundary layers; combustion research - tracking flame fronts, laminar burning velocities, and shock-induced combustion phenomena; heat transfer and natural convection - non-intrusive mapping of temperature gradients in confined geometries; material science - recent quantitative schlieren applications to stress fields in transparent solids extend its role beyond fluid dynamics.

Each of these domains continues to generate refinements in setup, processing, and interpretation, demonstrating Schlieren's adaptability to new scientific frontiers.

4. APPLICATIONS IN COMBUSTION AND HEAT TRANSFER

Beyond aerospace flows, schlieren imaging has played a crucial role in the study of combustion and heat transfer, where strong refractive index gradients are generated by temperature differences and chemical reactions. The non-intrusive nature of the method makes it especially well-suited for capturing flame fronts, convection cells, and shock–flame interactions, phenomena that are difficult to probe using intrusive diagnostics.

One of the earliest applications of schlieren in combustion was the study of laminar flame propagation, where knife-edge setups revealed flame front curvature and velocity in premixed mixtures. Subsequent refinements in shadowgraphy and rainbow schlieren enabled semi-quantitative estimation of burning velocities, by measuring displacement rates of refractive index gradients across flame zones [62]. These studies laid the foundation for modern optical combustion diagnostics.

High-speed schlieren has also been used to capture turbulent flame structures (Figure 11) and their interaction with shock waves, a phenomenon highly relevant to supersonic combustion and detonation studies. Using frame rates exceeding 50,000 fps, researchers have observed unsteady wrinkling, vortex–flame interactions, and flame destabilization, providing insights into flame stability limits and mechanisms of transition to detonation [63].

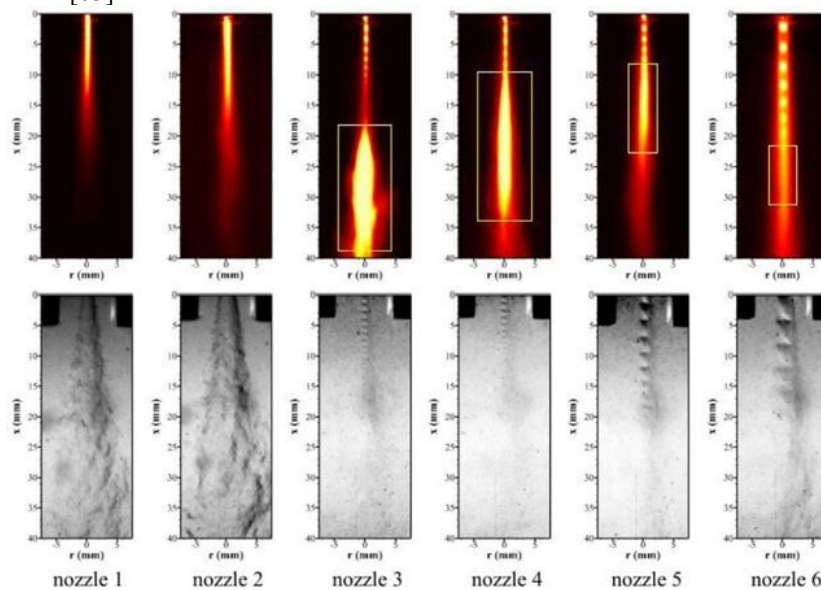


Figure 11. Simultaneous planar, time-resolved measurements of radiation intensity in a hot jet—using an H₂O band-pass filter ($2.58 \pm 0.03 \mu\text{m}$)—together with high-speed schlieren imaging reveal the shock structure of supersonic jets. The high-temperature region located downstream of the shock structure is highlighted by a yellow box [64].

In heat transfer research, schlieren and interferometry have been combined to study natural and forced convection. Holographic interferometry, in particular, allowed quantitative mapping of temperature gradients in confined geometries, while schlieren provided a fast, qualitative overview of convection cells and thermal plumes [65]. These results have advanced the understanding of cooling processes, electronic thermal management, and buoyancy-driven flows in enclosures.

The rainbow schlieren deflectometry (RSD) technique has proven especially valuable for combustion diagnostics, as it enables two-component measurement of refractive index gradients, directly related to temperature fields. This method has been applied to characterize methane-air Bunsen flames, showing close agreement with chemiluminescence imaging and numerical models [66]. More recently, RSD has been extended to low-luminosity flames, where conventional optical diagnostics are ineffective due to weak emission.

Background-Oriented Schlieren (BOS) has also found an important role in combustion studies. By tracking background distortions, BOS has been used to reconstruct density fields of premixed and non-premixed flames, as well as to measure buoyancy-induced convection around heated objects [67]. While BOS provides lower resolution than classical schlieren, its scalability and simple setup make it particularly attractive for large-scale combustion experiments and outdoor fire research.

Finally, schlieren has contributed to multiphysics studies, where combustion is coupled with acoustics or heat transfer. In thermoacoustic instability research, schlieren imaging has been synchronized with pressure transducers and microphones to reveal the coupling between flame oscillations and acoustic modes in combustion chambers [68]. Such studies are essential for gas turbine development, where controlling thermoacoustic instabilities is a major design challenge.

In summary, schlieren imaging has evolved into an essential diagnostic tool for combustion and heat transfer studies, enabling detailed observation of laminar and turbulent flame dynamics, convection patterns, and thermoacoustic interactions. Through extensions such as rainbow schlieren and BOS, the method has become increasingly quantitative, providing not only visual access but also measurable temperature and density fields.

5. EMERGING DIRECTIONS AND FUTURE PERSPECTIVES

As optical diagnostics continue to evolve, schlieren techniques are expanding well beyond their traditional domains. The integration with advanced imaging, computational methods, and data-driven algorithms is driving a new era where schlieren is not only a visualization tool but also a quantitative, predictive, and hybrid diagnostic system.

One of the most promising directions is the use of machine learning and artificial intelligence (AI) for schlieren image analysis. Instead of relying solely on manual interpretation or line-detection algorithms, AI can extract flow parameters such as Mach number, flow angle, and density gradients directly from schlieren sequences. Deep learning models trained on both experimental and computational datasets have demonstrated accuracy in reconstructing flow fields and identifying complex structures like shock–vortex interactions [60]. This trend suggests that AI-enhanced Schlieren will become an indispensable tool for real-time diagnostics in aerospace and combustion applications.

Another frontier is the application of schlieren to solid mechanics and material science, where light deflections reveal internal stresses rather than fluid density gradients. Recent quantitative schlieren methods have been applied to transparent polymers under shock loading, reconstructing stress fields with reasonable agreement to traditional velocimetry and interferometry [69]. This extension positions Schlieren as a non-contact diagnostic for high-rate material testing, bridging fluid dynamics and solid mechanics.

Tomographic approaches are also maturing, with time-resolved Schlieren tomography (TR-ST) offering 3D reconstructions of dynamic flows. Using multiple camera perspectives and advanced reconstruction algorithms, TR-ST captures volumetric evolution of turbulent jets, shock systems, and flame fronts, providing a new level of detail for validating computational models [70]. Such methods are particularly impactful in hypersonics, where three-dimensional unsteadiness governs vehicle performance and safety.

In parallel, miniaturized and field-deployable schlieren systems are gaining traction. Advances in high-intensity LEDs, compact optics, and digital cameras allow portable schlieren setups for outdoor or in-flight testing. For example, schlieren and BOS systems have been adapted for monitoring atmospheric disturbances, explosions, and even wildlife aerodynamics in natural environments [71]. These innovations democratize schlieren by making it accessible outside traditional laboratory setups.

Finally, the future of schlieren lies in hybridization—combining it with other diagnostics such as PIV, interferometry, and infrared imaging. Multi-modal platforms can simultaneously measure velocity, density, temperature, and stress fields, producing comprehensive datasets that capture the full complexity of fluid and

solid dynamics. Such integrated approaches are increasingly sought after in high-speed aerodynamics, combustion science, and energy applications [72].

In conclusion, schlieren and its derivatives are entering a transformative stage. By embracing AI-driven analysis, 3D tomography, hybrid diagnostics, and new application areas, the technique is evolving from a century-old visualization tool into a multifunctional, quantitative, and predictive platform. Its adaptability ensures that schlieren imaging will remain central to experimental fluid dynamics and beyond, guiding innovation in aerospace, energy, and materials research for decades to come.

6. COMPARATIVE ANALYSES OF OPTICAL FLOW VISUALIZATION METHODS

Beyond presenting each method individually, numerous studies have focused on direct comparisons between schlieren, shadowgraphy, interferometry, BOS, and rainbow variants. These comparative efforts highlight the strengths, weaknesses, and trade-offs of each approach, guiding researchers in selecting the most appropriate diagnostic technique for a given application.

One widely cited comparison was performed between shadowgraphy and schlieren, where both were applied to supersonic jets and flame propagation. Shadowgraphy was shown to excel at detecting shock positions and strong density gradients, owing to its sensitivity to the second derivative of refractive index. Conversely, schlieren offered superior contrast in regions with weaker gradients and provided more interpretable images for boundary layers and shear flows [73]. Together, these methods were considered complementary rather than mutually exclusive.

Comparisons between rainbow schlieren deflectometry (RSD) and calibrated monochrome schlieren have emphasized the balance between qualitative interpretability and quantitative rigor. RSD provides visually intuitive maps of gradient direction through color coding, but calibration complexity and chromatic aberrations reduce its precision. Calibrated knife-edge schlieren, on the other hand, achieves superior numerical accuracy at the cost of visual clarity and sensitivity to setup stability [66].

The advent of Background-Oriented Schlieren (BOS) prompted further comparative studies. BOS was consistently found to be advantageous for large-scale and outdoor applications, requiring only simple optics and relying heavily on post-processing. However, BOS often suffers from reduced spatial resolution compared to classical schlieren, especially in high-speed or turbulent flows. Several studies concluded that while BOS is ideal for scalability and non-intrusive setups, classical schlieren remains the gold standard for high-resolution laboratory studies [74].

Hybrid approaches, where multiple techniques are applied simultaneously, have provided the most insightful comparative datasets. For instance, combining BOS with PIV and schlieren revealed that BOS was effective in capturing large-scale density fields, while schlieren resolved fine-scale shear layers, and PIV quantified velocity structures. Such comparisons underscore the fact that no single method is universally superior, and the optimal choice depends on experimental goals, available resources, and the flow regime of interest [75]. A comparison between techniques is presented in Table 1.

Table 1. Comparison between techniques

Shadowgraphy	simple, robust, best for shocks and strong gradients.
Classical schlieren	versatile, high-contrast, ideal for jets and compressible flows.
Rainbow schlieren	visually intuitive but calibration-heavy.
BOS	scalable and flexible, but resolution-limited.
Interferometry	most quantitative, but delicate and complex.

Building on these comparisons, one can argue that the future lies in hybridization and cross-validation. By combining methods within the same experiment, researchers can harness the strengths of each technique

while mitigating their limitations. For example, integrating BOS for large-scale density mapping with calibrated schlieren for fine resolution provides a multi-scale picture unattainable by either method alone.

7. CONCLUSIONS AND OUTLOOK

The development of schlieren and related optical methods has been a defining element in the progress of experimental fluid dynamics and flow diagnostics. From their origins in the 19th century to their modern extensions in aerospace, combustion, and multiphase research, these methods have continuously evolved in both sophistication and application scope. By transforming refractive index variations—otherwise invisible to the naked eye—into measurable or interpretable optical signals, these techniques have allowed scientists and engineers to study flows that are otherwise inaccessible to intrusive instrumentation. Taken as a whole, the history and current landscape of schlieren research illustrate the paradigm shift from visualization to quantification, and from laboratory to field. Rather than being replaced by modern imaging techniques, schlieren has continuously reinvented itself, absorbing computational advances, hybridization strategies, and new physical contexts. Its central strength lies not in perfection but in adaptability: the ability to serve as both a rapid qualitative diagnostic and a precise quantitative tool, depending on the needs of the researcher. As experimental demands grow increasingly complex—ranging from hypersonic flight to microfluidics and multiphase systems—schlieren is positioned to remain a cornerstone of flow diagnostics. In conclusion, schlieren and related optical methods have matured into a unified framework for visualizing, measuring, and understanding flows across scales and disciplines. Their continuing evolution promises to keep them at the forefront of experimental fluid dynamics, providing essential insights into the invisible structures of fluids, gases, and even solids. The next generation of schlieren will not merely observe flow—it will measure, interpret, and predict it, bridging the gap between visualization, computation, and application.

The trajectory of schlieren and related methods suggests three key avenues for future research:

- AI and Machine Learning Integration - Automated feature detection, noise suppression, and real-time quantitative reconstruction will reduce reliance on manual calibration and subjective interpretation. Neural networks trained on synthetic and experimental data can extract flow fields directly from schlieren images.
- Tomographic and Volumetric Extensions - Time-resolved BOS tomography and multi-angle schlieren promise 3D reconstructions of turbulent structures, opening possibilities in studying fully three-dimensional and transient phenomena such as vortex breakdown, supersonic separation, or combustion instabilities.
- Miniaturization and Field Deployment - Advances in compact optics, LEDs, and high-speed consumer cameras enable portable schlieren systems for education, industry, and field experiments (including rocket launches and atmospheric studies). These democratize access to advanced diagnostics beyond specialized labs.

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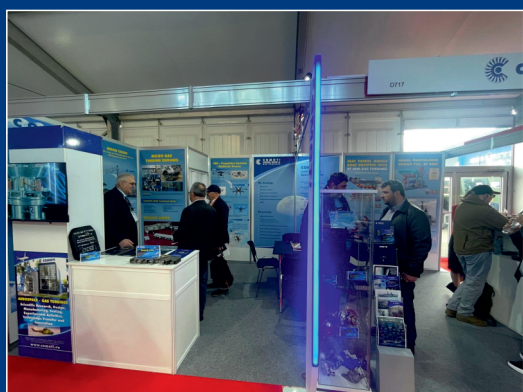
10th Edition

From 13–15 May 2026, the BSDA 2026 exhibition once again brought together leading companies, industry experts, and defence professionals to showcase the latest technologies and innovations shaping the future of security, aerospace, and defence in the Black Sea region. The event provided an important platform for collaboration, strategic partnerships, and the exchange of expertise across land, air, and naval domains.

COMOTI - Romanian Research & Development Institute for Gas Turbines actively participated in BSDA 2026 through multiple exhibition areas, highlighting its capabilities and ongoing developments in aerospace and defence technologies. Visitors could meet COMOTI representatives at the institute's main indoor stand located in Hall D, Booth 717, while the outdoor exhibition area featured several of the institute's UAV platforms, illustrating the practical results of its research and development activities.

COMOTI was also present within the booth of the Romanian Helicopters' Industry Association (ARIE), reaffirming its commitment to supporting the Romanian aerospace ecosystem and strengthening cooperation among national industry stakeholders.

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