



Shivani Sridhar

A Comparative Aerodynamic Feasibility Study of Fluidic Winglets for a
Conventional Transport Aircraft Wing

School of Aerospace, Transport and Manufacturing
MSc Aerospace Vehicle Design

MSC
Academic Year: 2024 - 2025

Supervisor: Dr. Amir Zare Shahneh



School of Aerospace, Transport and Manufacturing
Aerospace Vehicle Design

MSC
Academic Year: 2024 – 2025

Shivani Sridhar

A Comparative Aerodynamic Feasibility Study of Fluidic Winglets for a
Conventional Transport Aircraft Wing

Supervisor: Dr. Amir Zare Shahneh
January 2026

This thesis is submitted in partial fulfilment of the requirements for the
degree of MSc in Aerospace Vehicle Design

© Cranfield University year 2026. All rights reserved. No part of this
publication may be reproduced without the written permission of the
copyright holder.

Academic integrity declaration

I declare that:

- the thesis submitted has been written by me alone.
- the thesis submitted has not been previously submitted to this university or any other.
- that all content, including primary and/or secondary data, is true to the best of my knowledge.
- that all quotations and references have been duly acknowledged according to the requirements of academic research.

I understand that to knowingly submit work in violation of the above statement will be considered by examiners as academic misconduct.

A Comparative Aerodynamic Feasibility Study of Fluidic Winglets for a Conventional Transport Aircraft Wing

Shivani Sridhar*

Cranfield University1, Cranfield, Bedford, MK430AL, United Kingdom

A significant proportion of the total aerodynamic drag encountered by a commercial aircraft during cruise is induced drag. Conventional winglets have proven to effectively reduce the induced drag; however, they introduce additional structural weight and geometric complexity. As an alternative to conventional winglets, fluidic winglets have been proposed. The fluidic winglet concept involves the fluid injection/ suction at the wingtip to reduce vortices without major structural modifications. The present work examines the aerodynamic characteristics of a fluidic winglet concept applied to a representative narrow-body transport aircraft wing. By comparing multiple wingtip configurations under consistent cruise conditions, the study seeks to clarify the aerodynamic influence of fluidic injection on lift, drag, and vortex behaviour, and to position fluidic winglets relative to established passive wingtip devices within the broader context of induced-drag reduction research. The results highlight the potential of fluidic winglets as a non-structural induced drag-reduction technique for commercial transport aircraft.

Keywords: induced drag, vortex, fluidic winglet, narrow-body, wingtip, passive, lift.

Nomenclature

CW	=	Clean wing
BW	=	Wing with blended winglet
FW	=	Wing with fluidic winglet
C_L	=	Lift coefficient
C_D	=	Drag coefficient
V_∞	=	Freestream velocity (m/s)
V_j	=	Jet velocity (m/s)
ψ	=	Jet sweepback angle ($^\circ$)
δ	=	Jet dihedral angle ($^\circ$)
V_r	=	<i>Velocity ratio</i>
CAD	=	Computer aided design
CFD	=	Computational fluidic dynamics
AoA	=	Angle of attack ($^\circ$)
ρ_∞	=	Freestream density (kg/m ³)
ρ_j	=	Jet density (kg/m ³)
y^+	=	Target non-dimensional wall distance (m)
y	=	First layer thickness (m)
$\dot{m}_j$	=	Jet momentum flux
A_s	=	Slot area (m ²)
S_{ref}	=	Wing planform area (m ²)

I.Introduction

Improving the aerodynamic efficiency of commercial transport aircraft has long been a key objective in aerodynamic research, particularly through drag reduction, as this leads to improved fuel efficiency and lower operating costs. Among the different drag components, induced drag is closely associated with lift generation and the formation of wingtip vortices during cruise. These vortices arise from pressure differences between the upper and lower wing surfaces, resulting in energy loss in the wake and reduced overall efficiency [1,2].

To reduce induced drag, modern aircraft commonly employ conventional winglets, which have demonstrated clear aerodynamic benefits. However, winglets also introduce penalties in the form of additional structural weight, increased wing root bending moments, and manufacturing and certification constraints. These drawbacks have motivated the investigation of alternative, non-structural methods of vortex control. One such approach is the fluidic winglet concept, which uses controlled air injection or extraction near the wingtip to influence vortex formation and strength.[3,4].

Through active flow control, fluidic winglets modify the momentum distribution and vorticity in the wingtip region and may achieve drag reduction without significant geometric changes. Previous experimental and numerical studies have shown that suitably configured jet injection can weaken or diffuse the wingtip vortex and improve aerodynamic performance. However, their effectiveness depends strongly on parameters such as jet momentum, slot geometry, jet orientation, and operating conditions. In addition, the need to supply pressurised air introduces system complexity, power demand, and mass penalties, which may offset local drag reductions if not carefully considered. [5,6].

The objective of this study is to numerically investigate the aerodynamic performance of a fluidic winglet applied to a Boeing 737-800 wing under cruise conditions using CFD. A clean wing and a conventional blended winglet are first analysed to establish reference performance. Fluidic winglet configurations with different slot geometries are then evaluated, with emphasis on their effects on lift, drag, lift-to-drag ratio, and wingtip vortex behaviour. The results aim to clarify the potential advantages and limitations of fluidic winglets for drag reduction in commercial aviation.

II.Literature Review

A. Vortex and Induced Drag

Lift generation on wing results in a pressure-driven spanwise flow near the wingtip, causing the formation of trailing wingtip vortices. These vortices induce a downwash over the wing, reducing the effective angle of attack and tilting the lift vector rearwards, thereby producing induced drag [1]. Since wingtip vortices are an unavoidable

consequence of lift generation, research has focused on reducing their strength or modifying their structure to improve aerodynamic efficiency.

B. Conventional Winglets

Conventional winglets are vertical or near-vertical surfaces attached to the wingtip and are widely used on modern aircraft. Several configurations are in service, including blended winglets, split scimitar winglets, raked wingtips, and sharklets.

- Blended winglets, characterised by a smooth transition between the wing and winglet, reduce interference drag and provide improved lift-to-drag ratios compared with early sharp-junction designs. Derivative configurations such as sharklets are now common on narrow-body aircraft [3].
- Split scimitar winglets combine an upward winglet with a smaller downward element, redistributing vorticity and providing additional induced-drag reduction, particularly at higher lift coefficients. Their application is limited by increased structural complexity and manufacturing cost [1].
- Raked wingtips reduce induced drag by increasing effective wingspan and modifying the lift distribution rather than redirecting the vortex using a vertical surface. They are effective at cruise but are constrained by increased span and structural requirements [3].
- Canted winglets are inclined outward from the vertical, with aerodynamic performance strongly dependent on cant angle. Parametric studies show that optimisation is required to balance induced-drag reduction against structural and parasitic drag penalties [7].

Other advanced concepts, such as spiroid and multi-tip winglets, aim to split the primary vortex into several weaker vortices to promote faster wake dissipation. Although they show aerodynamic potential, their added complexity has limited commercial adoption [1].

C. Fluidic Winglets

Fluidic winglets represent an active method of induced-drag reduction by injecting pressurised air near the wingtip to influence vortex formation. Unlike fixed geometric devices, they modify the momentum and vorticity distribution in the wingtip region and may weaken the vortex without significant structural changes [6].

The concept is motivated by the limitations of passive winglets, which add structural mass, increase wing root bending moments, and introduce manufacturing constraints. Fluidic systems offer the possibility of on-demand operation, with activation primarily during cruise when induced drag is most significant [4].

Previous numerical and experimental investigations show that suitably oriented jet injection can weaken or displace the wingtip vortex, resulting in reduced induced drag and improved lift-to-drag ratio. Effective configurations generally involve spanwise or downstream-directed jets, whereas unfavourable orientations can intensify the vortex and increase drag [5,6].

Performance is strongly dependent on jet momentum, orientation, and slot geometry. An optimum injection condition is consistently reported, beyond which further increases in jet momentum produce diminishing benefits or aerodynamic penalties. Multi-slot and smoothly contoured slots have been found to provide better control than single or sharp-edged configurations [8,9].

Reported improvements from optimised fluidic winglets are typically modest, with lift-to-drag ratio increases of about 1–3% under specific cruise conditions. Comparisons with blended winglets indicate that passive devices often perform better at low angles of attack, while fluidic winglets may achieve similar performance at higher lift conditions [4,8]. A major limitation remains the system-level penalty associated with supplying pressurised air, as compressors, ducting, and power demand can offset aerodynamic gains and may lead to increased fuel consumption and reduced range [4].

D. Summary and Research Gap

The literature demonstrates that conventional winglets provide reliable and well-established reductions in induced drag but incur permanent structural penalties. Fluidic winglets offer a promising active alternative capable of modifying wingtip vortices without large geometric additions; however, their effectiveness is highly configuration-dependent and strongly influenced by system integration considerations.

Further research is required to optimise jet parameters, reduce system penalties, and validate numerical predictions through experimental testing. Comprehensive aircraft-level assessments remain essential to determine the viability of fluidic winglets for commercial transport aircraft applications [6].

III.Methodology

This study employs a computational approach to evaluate and compare the aerodynamic performance of conventional and fluidic winglet configurations applied to a commercial transport aircraft wing. The overall methodology comprises geometry development, numerical simulation, and aerodynamic performance assessment.

Three wing configurations were created using computer-aided design (CAD): a clean wing baseline (CW), a wing with a conventional blended winglet (BW), and a wing incorporating a fluidic winglet concept (FW). The fluidic winglet configurations include two jet slot geometries to examine the influence of slot design on flow control effectiveness. A series of computational fluid dynamics (CFD) simulations was conducted using a consistent numerical framework. The methodology includes computational domain generation, mesh development, grid independence assessment, solver setup, and post-processing. For the fluidic winglet cases, jet injection was represented using prescribed boundary conditions, with the actuation strength characterised by a jet momentum coefficient.

The aerodynamic performance of each configuration was evaluated and compared under representative cruise conditions. Detailed descriptions of the geometry, numerical setup, and parametric studies are presented in the following sections, and the overall workflow is summarised in the accompanying methodology flow chart.

IV.Model Geometry Design

Previous studies have shown that fluidic winglets can provide aerodynamic benefits on low-aspect-ratio wings, particularly in reducing induced drag and modifying wingtip flow. However, limited work has addressed their performance on medium- to high-aspect-ratio wings typical of commercial transport aircraft. As commercial aviation continues to expand, improving the aerodynamic efficiency of such aircraft remains an important research objective. An aircraft with publicly available geometric and limited aerodynamic data was therefore selected to allow numerical validation and meaningful comparison with existing studies.

Considering these aspects, a medium aspect ratio commercial aircraft wing was selected for the present numerical investigation. The wing configuration of the Boeing 737-800 was chosen as the baseline geometry for further analysis.

A. Geometry

The Boeing 737-800 has a medium aspect ratio wing fitted with blended winglets. The clean wing has a wingspan of approximately 34.32 m, while the wingspan including blended winglets is about 35.8 m [10,11]. Although general

wing planform characteristics and airfoil data for the Boeing 737 are publicly available, detailed geometric specifications of the blended winglet are not officially released.

Accordingly, the blended winglet geometry used in this study was developed using dimensional trends and design guidance reported in the literature, including sweep angles of around 25° and cant angles between 45° and 75° adopted on comparable narrow-body aircraft [2,12]. This approach allows a representative winglet geometry to be created while remaining consistent with published aerodynamic studies.

Three wing configurations were examined: a clean wing (CW), a wing with a blended winglet (BW), and a fluidic winglet (FW). The CW configuration served as the baseline model for the BW and FW cases. The principal geometric parameters of the wing and winglet are summarised in Table 1.

Table 1 Wing geometry

Parameters	Values
CW semi-span	17.16 m
BW semi-span	17.9 m
Root chord	7 m
Tip chord	1.6 m
Winglet sweep	26°
Cant angle	63°

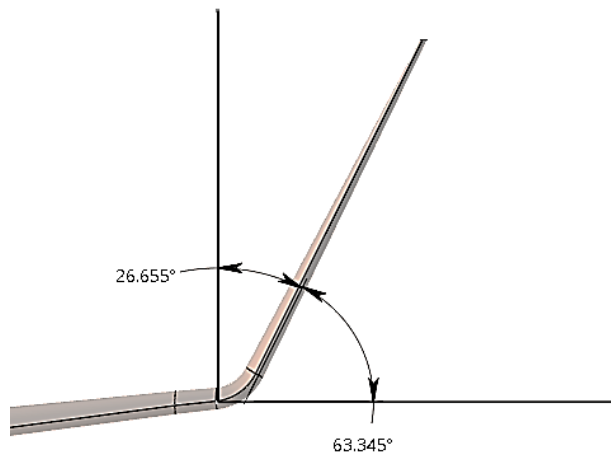


Figure 1 Blended winglet cant and sweep angles

B. Design

The CAD modelling of the wing geometries was carried out using CATIA V5 and 3DEXPERIENCE. To generate the wing planform, the root, mid-span, and outboard airfoil sections of the Boeing 737-800 wing were obtained from the *Airfoil Tools* database [13,14].

Top-view and front-view drawings obtained from publicly available sources [15]

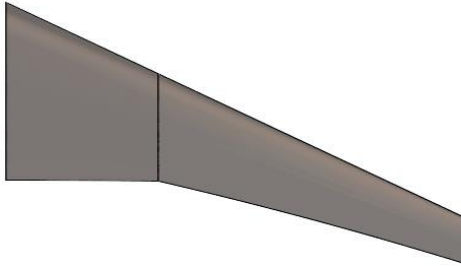


Figure 2 Baseline wing

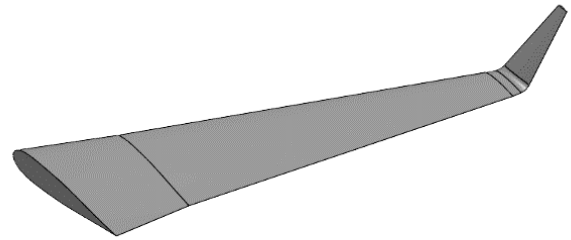


Figure 3 Blended winglet wing

C. Fluidic winglet slots

For the fluidic winglet configuration, active flow control was implemented using discrete jet injection slots located near the wingtip of the clean wing model. The objective was to examine the influence of slot geometry and jet characteristics on aerodynamic performance, with particular emphasis on wingtip vortex modification.

Two main slot geometries were considered: circular slots and obround slots. Circular and rectangular slot designs have been widely investigated in previous studies; however, circular slots have generally shown lower effectiveness than elongated geometries, especially at low jet momentum coefficients [16,17]. Rectangular slots, although more effective in terms of jet penetration and vortex interaction, may introduce sharp edges that can disturb the local flow field [9].

To address the limitations of both circular and rectangular slots, an obround slot geometry was adopted. This configuration combines semicircular ends with an elongated central section, enabling smoother jet development while preserving the benefit of increased slot length for improved interaction with the wingtip vortex.



Figure 4 Obround shaped slot

1. Circular Slot Configurations:

Three circular slot configurations were designed and analysed. Each configuration consisted of 14 circular slots arranged in-line along the wingtip region, with the following diameters:

- 10 mm diameter (cir_10)
- 20 mm diameter (cir_20)
- 30 mm diameter (cir_30)

These configurations were selected to evaluate the influence of slot diameter on jet momentum, mass flow rate, and overall aerodynamic effectiveness, while maintaining a consistent number and arrangement of slots.

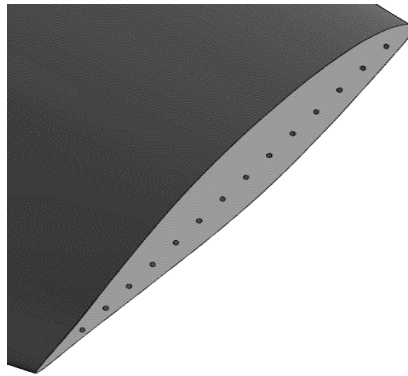


Figure 5 Circular slotted FW

2. Obround Slot Configurations:

Initially, two obround slot configurations were investigated to explore the upper limits of slot effectiveness:

- 900 mm length $\times$ 25 mm width (ob_900;25)
- 1100 mm length $\times$ 25 mm width (ob_1100;25)

These configurations were intended to assess the maximum potential aerodynamic benefit achievable through elongated slot designs with high jet momentum.

Consequently, two additional obround slot configurations were developed to achieve more realistic jet momentum coefficients while maintaining effective flow control:

- 900 mm length $\times$ 20 mm width (ob_900;20)
- 1000 mm length $\times$ 20 mm width (ob_1000;20)

These refined configurations allowed for a more practical assessment of fluidic winglet performance, balancing aerodynamic effectiveness with feasible actuation requirements.



Figure 6 Obround slotted FW

V. Jet Actuation System for Fluid Injection

Two main types of fluidic winglets are reported in the literature: fluid injection (blowing) and fluid suction. Injection systems introduce pressurised air near the wingtip to weaken or displace the vortex core, whereas suction systems remove flow from the wingtip region. Previous studies show that injection-based systems provide stronger and more reliable vortex control, while suction-based concepts generally offer limited authority and require complex duct routing. Therefore, only injection-type fluidic winglets are considered in the present study [4,9,16].

The selection of a suitable system architecture aims to provide sufficient jet momentum while limiting additional mass, power demand, and fuel penalties. Several concepts have been proposed in the literature.

- **Engine bleed-air systems:** These extract pressurised air from the engine and route it to wingtip slots. Their main advantage is the availability of a pressurised air source on conventional aircraft. However, bleed extraction reduces engine efficiency and requires extensive ducting and thermal management, increasing system mass and complexity [9,18].
- **Ram-air supply systems:** These use freestream air captured through an inlet and directed to the injection slots, avoiding continuous engine bleed extraction. Their main disadvantage is the additional drag and pressure losses in the ducting, which limit achievable jet momentum without further compression [18,19].

- **Electric compressor-driven systems:** Electrically powered compressors ingest and compress ambient air before injection, enabling on-demand jet control and compatibility with more-electric aircraft concepts. However, added component mass, electrical power demand, and cooling requirements may reduce the net aerodynamic benefit [3,18].
- **Pressurised tank systems:** Compressed air stored in onboard tanks is supplied to the wingtip slots. This approach is independent of the engine but requires structural reinforcement and long ducting runs, leading to significant mass and pressure-loss penalties [9,19].
- **HLFC-integrated systems:** These redirect air extracted by hybrid laminar flow control systems to the wingtip slots, reducing the need for separate compressors and long ducting. This option is limited to aircraft equipped with HLFC technology and requires careful system integration [4,19].
- **Venturi-based pressure control systems:** These exploit local pressure differences in the external flow to drive air through the slots without powered compression. Although mechanically simple and low in power demand, the achievable jet momentum is limited by the available pressure gradient, restricting effectiveness for strong vortex control at cruise [19].

Among these concepts, HLFC-integrated and electric compressor-driven systems are considered the most efficient in principle, as they avoid continuous engine bleed extraction while allowing controllable injection [3,4,19]. However, the Boeing 737-800 is not equipped with HLFC hardware, making this option unsuitable for practical use.

For a 737-800-based application, the literature identifies engine bleed-air supply with pressure regulation as the most realistic architecture, as it uses an existing pressurised air source and avoids the mass penalties associated with storage tanks and long ducting systems [9,18]. Its principal limitation remains the reduction in engine efficiency associated with bleed extraction.

As the present work focuses on aerodynamic feasibility rather than detailed system integration, an idealised injection system was adopted in which the jet flow is prescribed directly at the wingtip slots. This approach is consistent with previous aerodynamic studies and enables the influence of jet parameters to be assessed without introducing additional system-level uncertainties [3,6,17].

VI.CFD analysis

A. Computational Domain

A three-dimensional enclosure was created around the wing to represent the external flow for a semi-span configuration. The inlet boundary was located at a distance of 10 times the wing semi-span upstream of the leading edge, while the outlet boundary was positioned 20 times the wing semi-span downstream of the trailing edge to allow adequate wake and vortex development. The upper and lower boundaries were placed 10 chord lengths above and below the wing, and the outboard boundary was set at 2 times the wing semi-span from the wingtip. A symmetry boundary condition was applied at the wing root plane.

A rectangular computational domain was selected instead of a C-type domain due to its simplicity and suitability for complex three-dimensional geometries. This domain facilitates mesh generation and straightforward boundary condition assignment. By positioning the far-field boundaries sufficiently far from the wing, the flow may be treated as effectively unconfined, ensuring negligible blockage and boundary effects for all configurations considered.

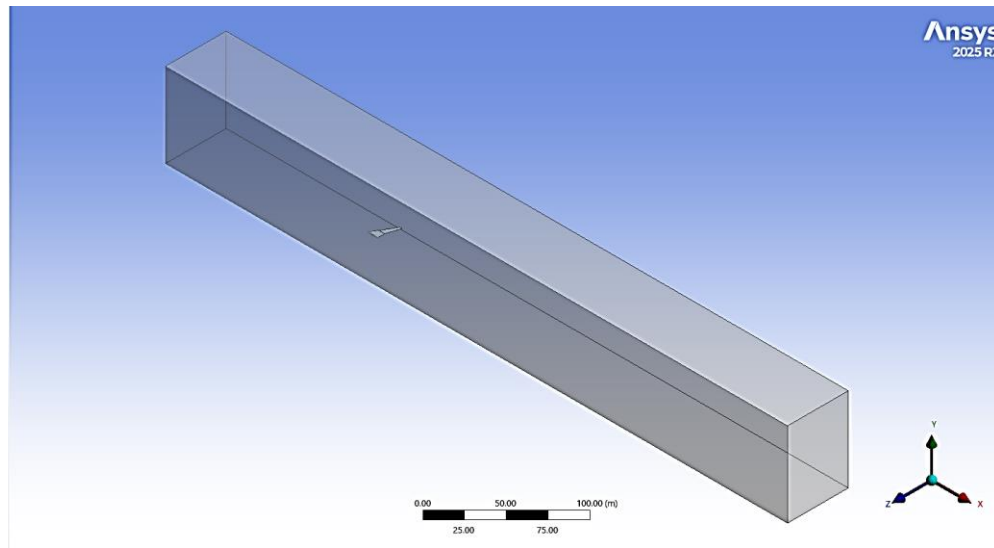


Figure 7 Enclosure representing fluid domain

B. Ansys Meshing

Mesh generation was performed using ANSYS Meshing. Although ICEM CFD is capable of producing high-quality structured meshes, it is comparatively complex and time-consuming. ANSYS Meshing was therefore selected as it provides a more efficient and user-friendly workflow while still allowing sufficient control over mesh quality for external aerodynamic simulations.

An unstructured tetrahedral mesh was used for the computational domain, which is a simple yet suitable approach for complex three-dimensional geometries such as wingtip devices. Local mesh refinement was applied in key regions, including the wing surfaces, wingtip area, and jet injection slots, using face sizing controls to ensure adequate

resolution of boundary-layer development and vortex formation. The mesh quality criteria and the mesh quality for the clean wing configuration are presented in Table 2.

Table 2 Mesh quality criteria

Mesh Metric	Criteria	Maximum	Minimum	Average	Failing elements
Aspect Ratio (general flow region)	<50	86.895	1.1621	4.8407	0.04%
Aspect Ratio (boundary layer prism cells)	<150				
Skewness	<0.85	0.96435	0.00015	0.25148	~0%
Orthogonal Quality	0.1-1	0.99952	0.036	0.74753	~0%

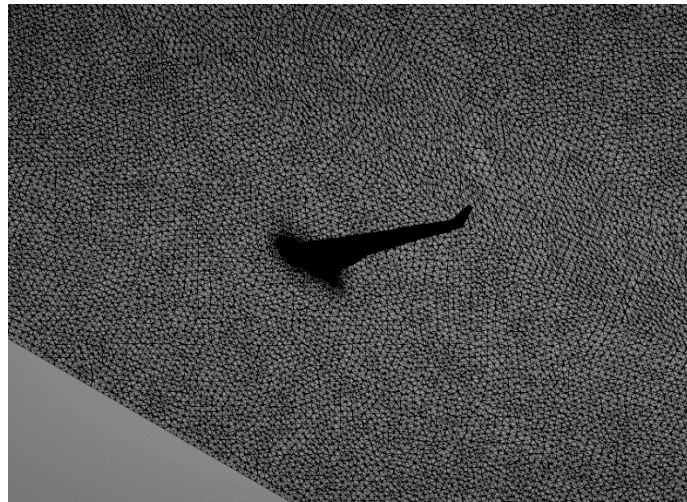


Figure 8 Face sizing of BW

Prism layers were generated on the wing surface using the first layer thickness method in the inflation tool. A first layer thickness of 0.0016 m with 15 inflation layers and 1.2 as the growth rate was applied. This resulted in the wing wall y^+ between the range of 5-300. The estimation of the first layer thickness done using the Sutherland constant is shown in the Appendix B.

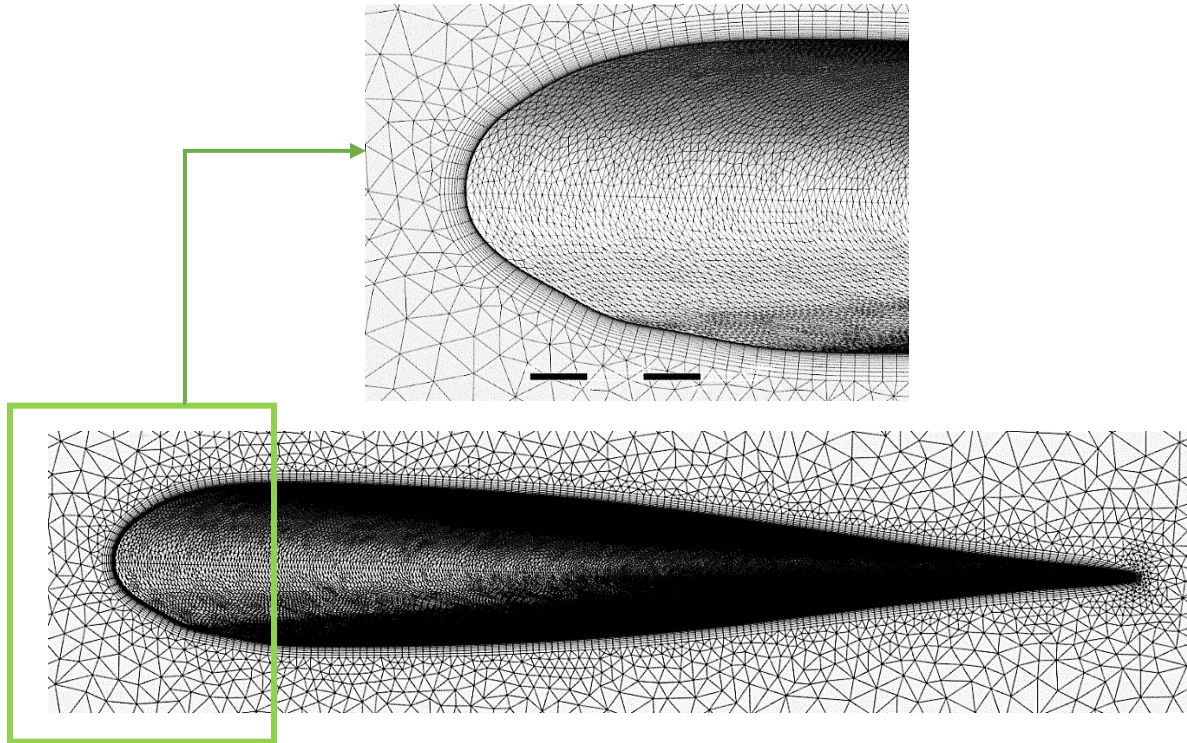


Figure 9 Prism layer around the wing

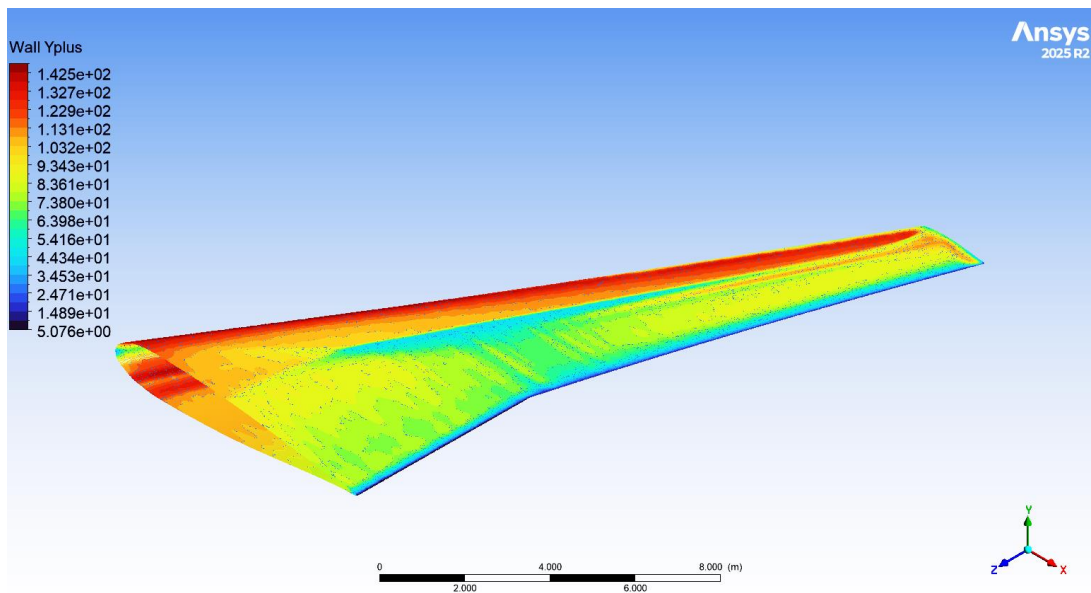


Figure 10 Wing wall Y+ range for CW

A grid independence study was performed to ensure that the numerical results were not affected by mesh density. Three meshes were generated for the clean wing configuration: coarse (3 million cells), medium (7 million cells), and fine (10 million cells). Mesh refinement was achieved by reducing the global element size and increasing resolution

in key regions, particularly over the wing surface and wingtip area, while maintaining the same meshing strategy and quality criteria.

Lift coefficient, drag coefficient, and lift-to-drag ratio were used to assess mesh independence. The differences between the medium and fine meshes were within approximately 1%, indicating negligible sensitivity to further refinement. Consequently, the medium mesh was adopted for all subsequent simulations as it provided an appropriate compromise between accuracy and computational cost.

C. Fluent Setup

3. Model and Material

All simulations were performed in ANSYS Fluent using a steady-state, pressure-based solver suitable for subsonic external aerodynamics. The $k-\omega$ SST turbulence model was employed for its reliability in capturing adverse pressure gradients, flow separation, and wake development near the wingtip and winglet regions. Air density was modelled as an ideal gas to represent cruise conditions, and temperature-dependent viscosity was defined using Sutherland's law.

4. Boundary Conditions

A symmetry boundary condition was applied at the wing root plane to model a semi-span configuration and reduce computational cost. The wing and winglet surfaces were defined as no-slip walls. All remaining outer boundaries of the computational domain were assigned pressure far-field boundary conditions to represent an unbounded external flow. The pressure far-field condition was chosen instead of a velocity inlet because it allows the freestream flow to be specified sufficiently far from the wing, reducing the risk of artificial boundary effects. This approach also enables consistent definition of freestream pressure, temperature, and velocity.

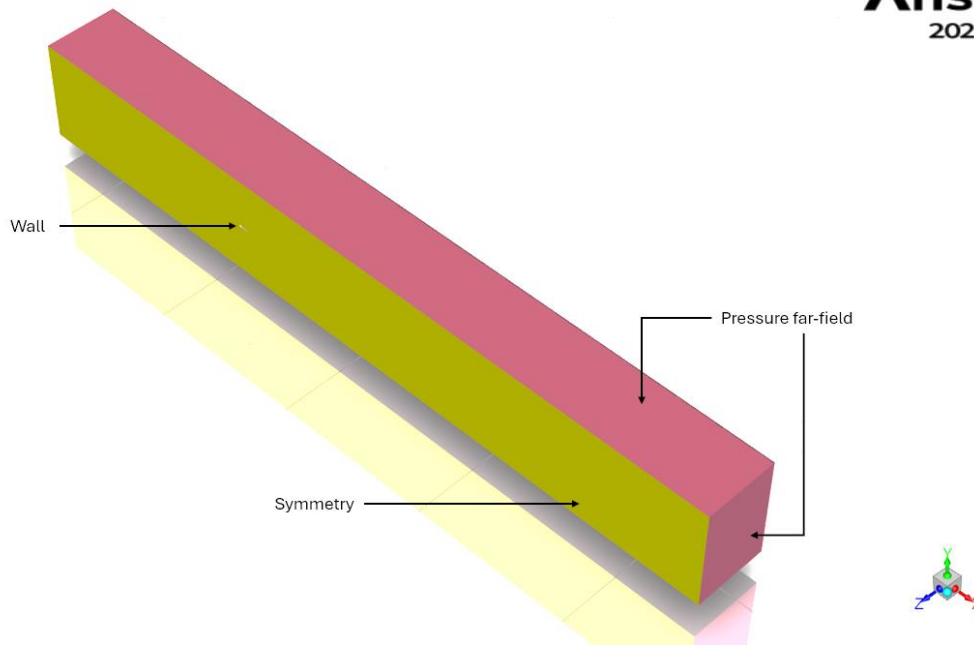


Figure 11 Boundary conditions

For the FW cases, a velocity inlet boundary condition was applied at the injection slots to model the jet flow entering the domain. The velocity components were defined based on the jet velocity, jet sweep angle, and jet dihedral angle, while also accounting for the wing angle of attack, in order to represent the direction and magnitude of the injected flow accurately.

5. Reference Values

All simulations were conducted under cruise flight conditions corresponding to an altitude of 35,000 ft, with a freestream velocity of 230 m/s. The operating pressure was set to the standard atmospheric pressure at this altitude, and the corresponding freestream temperature and density were defined in the reference values using ISA standard atmosphere data. This ensured that the aerodynamic coefficients were evaluated under representative cruise conditions. The mean aerodynamic chord (MAC) and reference area of the wing were set to 3.96 m and 62.3 m², respectively, based on values obtained from reference studies and the CAD planform area [10].

6. Initialisation and Run

Hybrid initialisation was employed, with preliminary simulations run for up to 8000 iterations to examine solver convergence. These test cases showed that the lift and drag coefficients reached steady values after approximately

3000 iterations. Consequently, the maximum number of iterations for subsequent simulations was reduced to 5000 to ensure convergence while limiting unnecessary computational expense.

D. CFD post-processing

Pressure and vorticity contours were used to compare the strength and behaviour of the wingtip vortices for each configuration. To examine the vortex structure, contours of the velocity invariant Q and the velocity curl in the x -direction were plotted on a plane downstream of the wing trailing edge in the wingtip wake region. The Q -criterion was used to identify vortical structures, while the velocity curl provided a measure of local rotational motion and an indication of vortex core strength. In addition, the vortex core region tool was applied to evaluate and compare the distribution of vorticity over the wing surface.

Pressure contours were also examined on the same wake plane to assess the pressure field associated with the vortex core. Since wingtip vortices are characterised by a low-pressure centre, changes in this distribution indicate variations in vortex strength and location.

VII. Fluidic Winglet Optimisation

Various cases were simulated by varying key fluidic injection parameters, namely the jet velocity, jet sweepback angle, jet dihedral angle, and the coefficient of jet momentum. These parameters were selected based on trends and sensitivities reported in previous investigations of fluidic winglets and active wingtip flow control and were systematically varied in order to identify an efficient and practically feasible configuration for the present wing geometry.

A. Jet Velocity:

The jet velocity was varied using the velocity ratio (V_r), defined as the ratio of jet exit velocity to freestream velocity. This non-dimensional parameter allows consistent comparison between different operating conditions and is commonly used in fluidic winglet studies.

Based on literature findings, three velocity ratios were selected: 1.05, 1.15, and 1.25. A velocity ratio of 1.15 has been shown to weaken the wingtip vortex and improve lift-to-drag ratio without excessive jet power requirements [4,17] and was therefore used as the reference case.

A lower velocity ratio of 1.05 was considered to examine whether vortex control could be achieved with reduced jet momentum, which would be beneficial from a power and system efficiency perspective. A higher velocity ratio of

1.25 was also investigated to determine whether increased jet momentum would enhance vortex weakening or result in diminishing aerodynamic returns due to increased mixing losses and flow disturbance.

B. Jet Sweepback Angle (ψ):

The jet sweepback angle is defined as the angle between the jet injection direction and the local chordwise direction of the wing in the horizontal plane. It governs the spanwise component of the injected flow and its interaction with the wingtip vortex formation process. Previous studies have shown that both 0° [4] sweepback and larger angles, such as 45° [3], can reduce vortex strength depending on wing configuration and operating condition.

Accordingly, sweepback angles of 0° and 45° were selected to represent configurations reported as effective in earlier work, while an intermediate angle of 30° was included to examine whether a compromise orientation could provide balanced performance and to assess non-linear trends in vortex response.

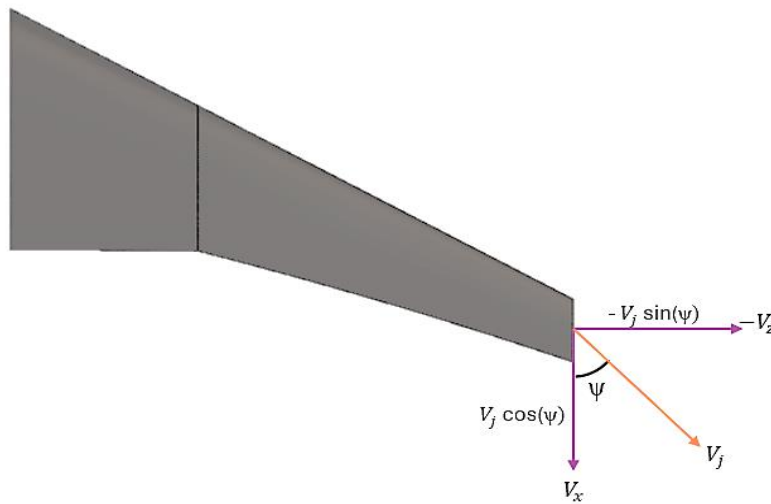


Figure 12 Local jet velocity components at a sweep angle

C. Jet Dihedral Angle (δ):

The jet dihedral angle is defined as the inclination of the injected jet relative to the wing plane in the vertical direction, with a positive value corresponding to upward-directed injection. This parameter determines whether the injected flow displaces the vortex core away from the wing surface or enhances near-surface rotational flow.

Reported studies indicate that small upward injection angles of approximately 10° – 15° can displace the vortex core and reduce wake vorticity [17], while a dihedral angle of 5° produced the most favourable lift-to-drag ratio among the tested cases [19]. Based on these findings, the jet dihedral angle was varied between 0° and 5° only for configurations

that showed favourable performance under variations in jet velocity and sweepback angle. This approach was used to assess whether a small upward inclination further improves vortex control compared with horizontal injection.



Figure 13 Local jet velocity components at a dihedral angle

It should be noted that the jet velocity must be resolved into the global cartesian coordinate system while accounting for the jet sweepback angle, jet dihedral angle, and the wing angle of attack. Since the wing is inclined relative to the freestream at a non-zero angle of attack, a further coordinate transformation is required to express the jet velocity in the global reference frame.

D. Coefficient of jet momentum

The coefficient of jet momentum is defined as the ratio of jet momentum flux ($\dot{m}_j$) to the freestream momentum flux over a reference wing area and provides a non-dimensional measure of jet strength relative to the main flow.

The derived, simplified relation of coefficient of jet momentum including the slot area (A_s), wing planform area (S_{ref}) and the velocity ratio (V_r)

$$C_\mu = \frac{2A_s V_r^2}{S_{ref}} \quad 1$$

This parameter is important for comparing different slot geometries and injection conditions, as it accounts for variations in both jet velocity and slot area [16].

VIII. Results and discussion

A. Convergence Criteria

For external aerodynamic flow simulations around wings, best practice guidelines indicate that residuals should be reduced by at least three to four orders of magnitude, with values around 10^{-4} commonly accepted for steady-state solutions when force coefficients have also converged [20]. However, residual reduction alone is not sufficient to confirm convergence.

In the present study, the convergence criterion for all residuals was set to 10^{-4} . These included the residuals for continuity, x-velocity, y-velocity, z-velocity, turbulent kinetic energy (k), and specific dissipation rate (ω). During the simulations, all residuals except continuity converged below the specified limit. The continuity residual stabilised at approximately 2×10^{-3} , as shown in Figure 14.



Figure 14 Converged residuals plot

This behaviour was considered acceptable because the lift coefficient (C_L) and drag coefficient (C_D) reached steady values and showed no significant change with further iterations. As these aerodynamic coefficients were the primary quantities of interest in the present work, their stability was taken as the main indicator of solution convergence. In addition, the residual plots were smooth and flat, with only minor oscillations observed in the ω residual. These oscillations were repetitive and of low magnitude, indicating a stable solution rather than numerical divergence.

B. C_D , C_L and L/D

The lift-to-drag ratio and vortex behaviour of the CW and BW were examined over angles of attack of 0° , 2.5° , 5° , and 10° to represent both cruise and off-design conditions. For the FW, the parametric study was initially

performed at 2.5° , corresponding to cruise where induced drag is most significant. After identifying the most effective slot configuration, the selected FW case was then analysed at 0° , 5° , and 10° to allow direct comparison of its aerodynamic performance and vortex characteristics with the CW and BW over the same angle-of-attack range.

The lift and drag coefficient plots shown in Figure 16 and Figure 15 respectively, exhibit typical converged aerodynamic behaviour, with smooth trends and minimal oscillations.

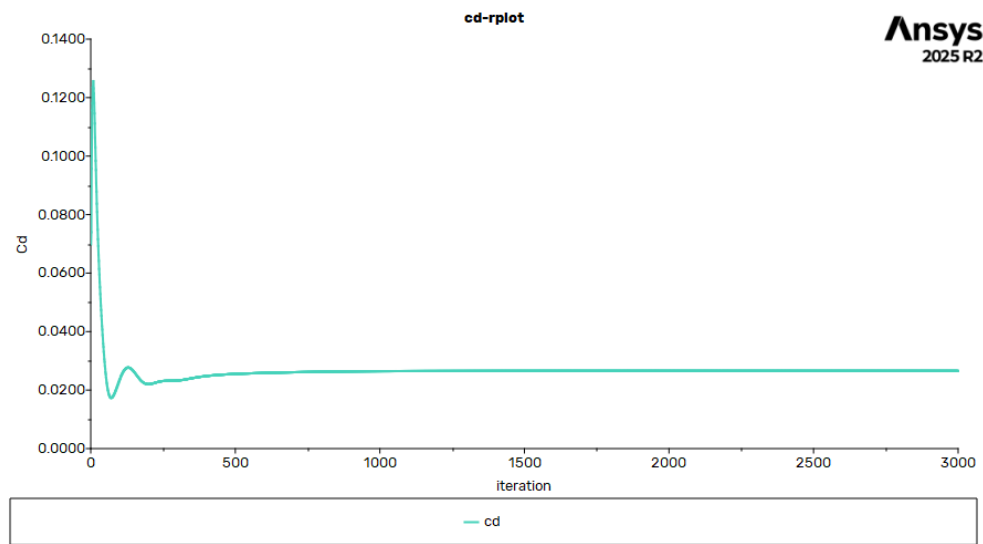


Figure 15 Drag coefficient plot

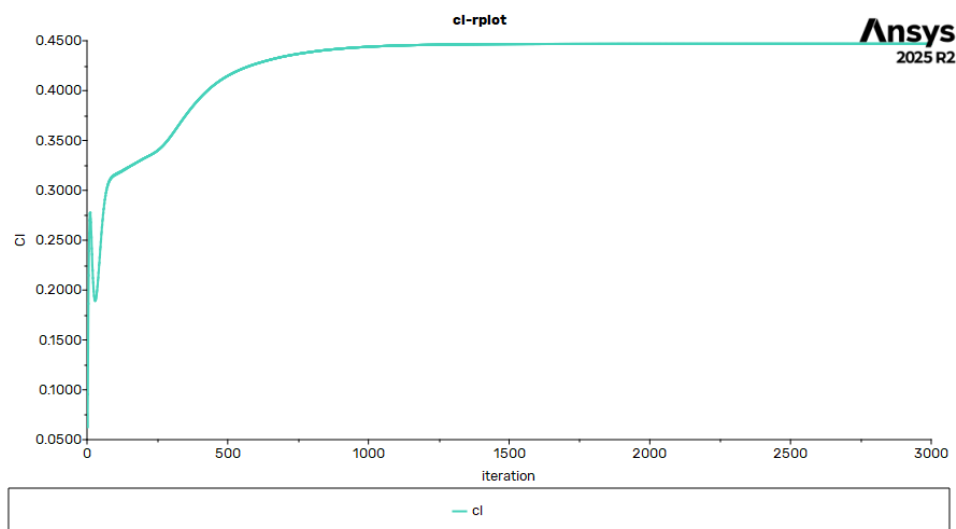


Figure 16 Lift coefficient plot

1. Aerodynamic characteristics of CW and BW

Table 3 shows the variations in the lift and drag for the CW and BW at different angles of attack, in cruise condition.

Table 3 Effect of AoA on CW and BW

Wing Configuration	AoA (°)	C_D	C_L	L/D
CW	0	0.013200	0.130500	9.886364
	2.5	0.027906	0.465430	16.678492
	5	0.067600	0.742880	10.989349
	10	0.185800	1.105000	5.947255
BW	0	0.052141	0.651613	12.497035
	2.5	0.029675	0.507560	17.103960
	5	0.052516	0.582703	11.095829
	10	0.861779	5.076454	5.890667

It can be observed that at an angle of attack of 2.5° under cruise conditions, the maximum lift-to-drag ratio is obtained, with a slightly lower value occurring at 5° . At low angles of attack such as 2.5° , the wing produces sufficient lift while maintaining relatively low drag. As the angle of attack increases, lift initially rises almost linearly, but drag grows more rapidly due to stronger pressure gradients, thicker boundary layers, and increased induced drag from stronger wingtip vortices. Consequently, although the lift at 5° is greater than at 2.5° , the corresponding increase in drag is proportionally larger, leading to a reduced lift-to-drag ratio compared with the 2.5° case.

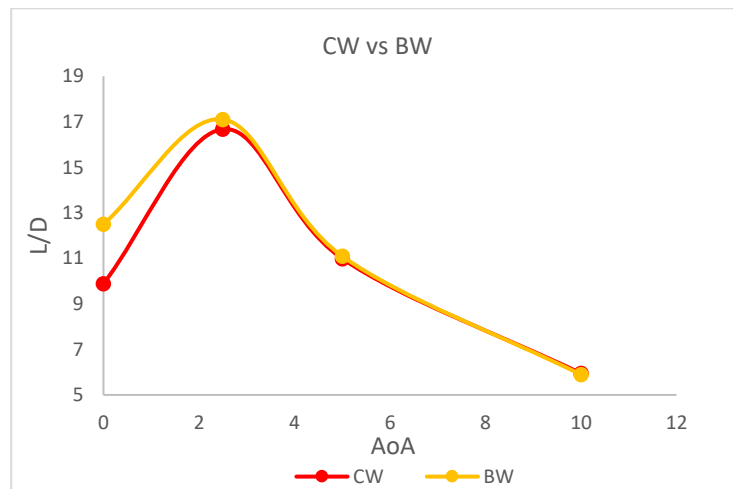


Figure 17 Comparison of L/D ratio between CW and BW

2. Aerodynamic characteristics of FW

Table 4 shows the variations in the lift and drag of the FW for the different slot geometries with varying jet velocity and 0° sweep and dihedral angle.

Table 4 Effect of jet velocity

Slot	Velocity Ratio (V_r)	Jet Sweep Angle φ ($^\circ$)	Jet Dihedral Angle δ ($^\circ$)	C_D	C_L	L/D
cir_10	1.15	0	0	0.026567	0.446860	16.820115
	1.05	0	0	0.026567	0.446858	16.820269
	1.25	0	0	0.026567	0.446856	16.820084
cir_20	1.15	0	0	0.026578	0.446960	16.816916
	1.05	0	0	0.026579	0.446960	16.816284
	1.25	0	0	0.026578	0.446960	16.816916
cir_30	1.15	0	0	0.026589	0.446140	16.779119
	1.05	0	0	0.026579	0.446550	16.800858
	1.25	0	0	0.026579	0.44655	16.800858
ob_900;20	1.15	0	0	0.026502	0.446010	16.829296
	1.05	0	0	0.026503	0.446020	16.829038
	1.25	0	0	0.026503	0.446010	16.828661
ob_1000;20	1.15	0	0	0.026530	0.446370	16.825104
	1.05	0	0	0.026530	0.446370	16.825104
	1.25	0	0	0.026530	0.446380	16.825481
ob_900;25	1.15	0	0	0.026430	0.445040	16.838441
	1.05	0	0	0.026429	0.445040	16.839078
ob_1100;25	1.15	0	0	0.019120	0.321640	16.822176
	1.05	0	0	0.026494	0.445720	16.823432

It can be observed that among the circular slot geometries, the cir_10 and cir_30 configurations produced the highest lift-to-drag ratio at a velocity ratio of 1.05, whereas the cir_20 configuration achieved its maximum performance at a velocity ratio of 1.15. For the obround slot geometries, the ob_900;25 configuration yielded the highest lift-to-drag ratio at a velocity ratio of 1.05 when compared with the other obround slot cases.

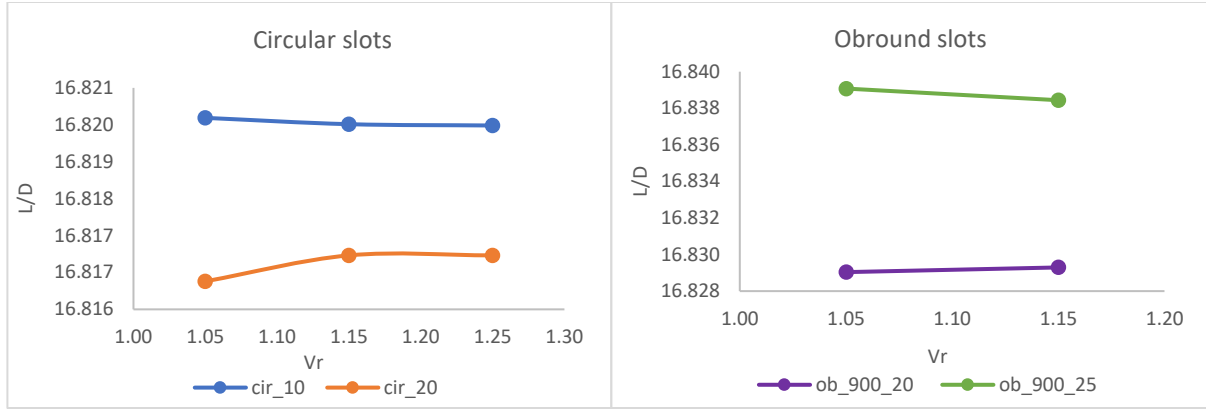


Figure 18 Comparison of L/D between circular and obround slots

A comparison between the best-performing circular and obround slot configurations indicates that, although the obround slot produces a higher lift-to-drag ratio, this improvement is mainly due to a reduction in drag coefficient of approximately 0.5%, accompanied by a concurrent decrease in lift coefficient. This indicates that the increase in aerodynamic efficiency arises primarily from drag reduction rather than lift enhancement.

The next set of analyses was carried out by maintaining a constant velocity ratio, corresponding to the optimum value identified for each slot geometry, while varying the jet sweep angle. Table 5 presents the resulting variations in lift and drag coefficients for the fluidic winglet configurations at different jet sweepback angles.

Table 5 Effect of jet sweepback angle

Slot	Velocity Ratio (V_r)	Jet Sweep Angle φ ($^\circ$)	Jet Dihedral Angle δ ($^\circ$)	C_D	C_L	L/D
cir_10	1.05	0	0	0.026567	0.446858	16.820269
	1.05	30	0	0.026549	0.446410	16.814569
	1.05	45	0	0.027112	0.447736	16.514473
cir_20	1.15	0	0	0.026578	0.446960	16.816916
	1.15	30	0	0.026575	0.446830	16.813923
	1.15	45	0	0.026575	0.446760	16.811289
cir_30	1.05	0	0	0.026579	0.446550	16.800858
	1.05	30	0	0.026580	0.446380	16.793830
	1.05	45	0	0.026579	0.446440	16.796719
ob_900;20	1.15	0	0	0.026502	0.446010	16.829296
	1.15	30	0	0.026508	0.446020	16.825864
	1.15	45	0	0.026517	0.446030	16.820530
ob_900;25	1.05	0	0	0.026429	0.445040	16.839078
	1.05	30	0	0.026479	0.445300	16.817100

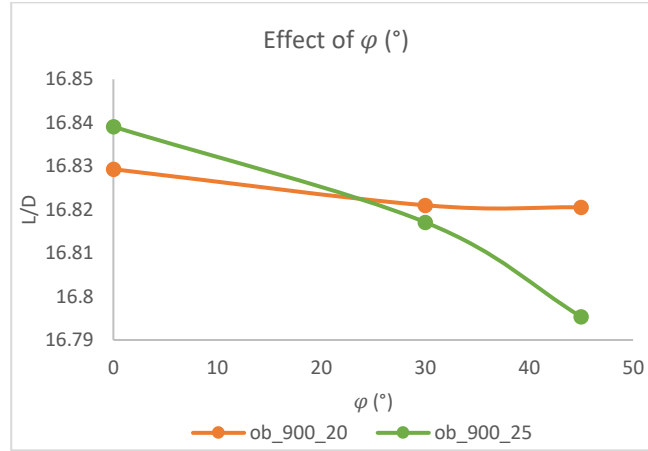


Figure 19 Comparison of L/D among obround slots

It was observed that several slot configurations achieved their optimum performance at a jet sweep angle of 0°. This is likely due to improved alignment of the injected jet with the local flow direction near the wingtip, enabling more effective vortex interaction. Therefore, sweep angles of 30° and 45° were excluded from further analysis.

Table 6 summarises the corresponding lift and drag coefficients for the fluidic winglet with a jet dihedral angle of 5° and sweep angle of 0° with the corresponding optimum jet velocity.

Table 6 Effect of dihedral angle

Slot	Velocity Ratio (Vr)	Jet Sweep Angle ϕ (°)	Jet Dihedral Angle δ (°)	C_D	C_L	L/D
cir_10	1.05	0	5	0.026567	0.446860	16.820115
cir_20	1.15	0	5	0.026578	0.446960	16.816752
cir_30	1.05	0	5	0.026579	0.446550	16.800858
ob_900;20	1.15	0	5	0.026503	0.446030	16.829416
ob_900;25	1.05	0	5	0.026429	0.445040	16.839078

It can be observed that the overall performance of the slot configurations decreases when the jet dihedral angle is increased from 0° to 5°. However, for the 900 × 25 mm obround slot, the aerodynamic characteristics at a dihedral angle of 5° remain essentially unchanged compared with the 0° case.

Among all the slot geometries investigated over the range of jet parameters, the obround slot with dimensions 900 × 25 mm produced the highest lift-to-drag ratio and was therefore selected as the optimal FW arrangement.

The selected FW configuration was then simulated at angles of attack of 0° , 5° , and 10° to evaluate its aerodynamic performance over a wider operating range and to allow direct comparison with the CW and BW configurations. The corresponding results are presented in Table 7.

Table 7 Effect of AoA on FW

Wing Configuration	AoA ($^\circ$)	C_D	C_L	L/D
FW	0	0.012999	0.1328598	10.220771
	2.5	0.026429	0.445040	16.839078
	5	0.065562	0.726160	11.075928
	10	0.174020	1.015600	5.836111

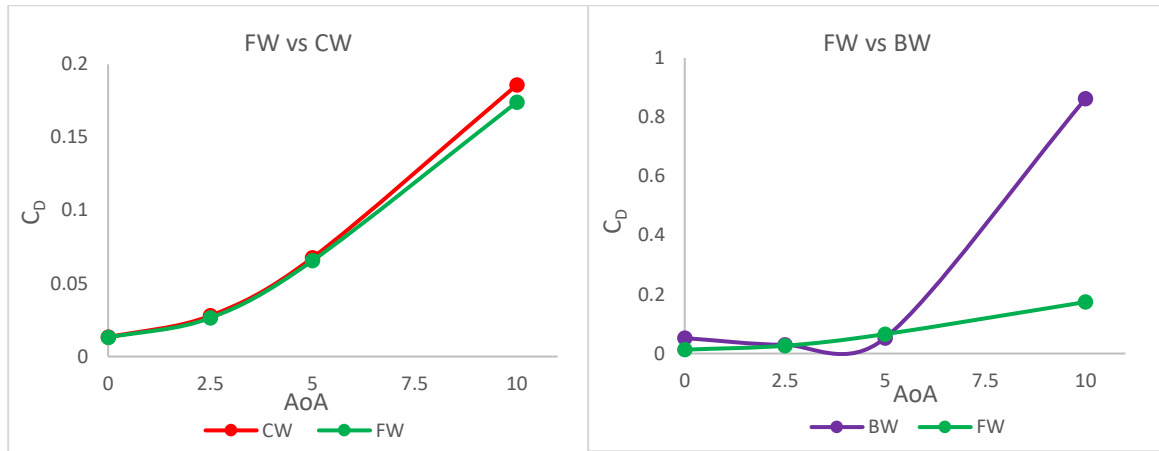


Figure 20 Comparison of drag of FW with CW and BW

The FW provides greater drag reduction than both the CW and the BW, with approximately 5% reduction compared to the CW and 10% compared to the BW at an angle of attack of 2.5° . This improvement is attributed to the momentum added by the injected jet, which modifies the local flow near the wingtip and reduces induced drag without introducing additional wetted area or structural surfaces. In contrast, the blended winglet achieves drag reduction through geometric extension of the wing, which also introduces additional profile and interference drag. Consequently, the FW offers a larger net drag reduction at this operating condition.

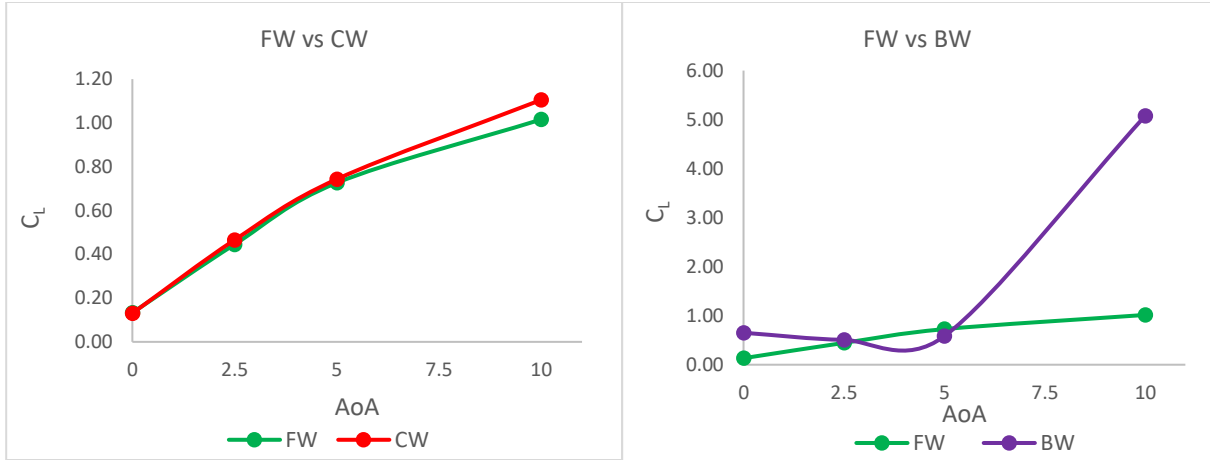


Figure 21 Comparison of lift of FW with CW and BW

In terms of lift, the FW exhibits a slight reduction compared with both the CW and the BW, with approximately 4% and 10% decrease in lift, respectively, at an angle of attack of 2.5° . This behaviour is associated with modification of the local flow near the wingtip caused by the injected jet, which alters the pressure distribution and reduces the effective lifting contribution of the outer wing region.

However, the reduction in lift is accompanied by a proportionally larger reduction in drag. As a result, the overall lift-to-drag ratio of the FW remains favourable relative to the CW, despite the decrease in lift. This indicates that the injected momentum mainly reduces drag-producing effects rather than significantly increasing lift, leading to an overall aerodynamic benefit at this operating condition.

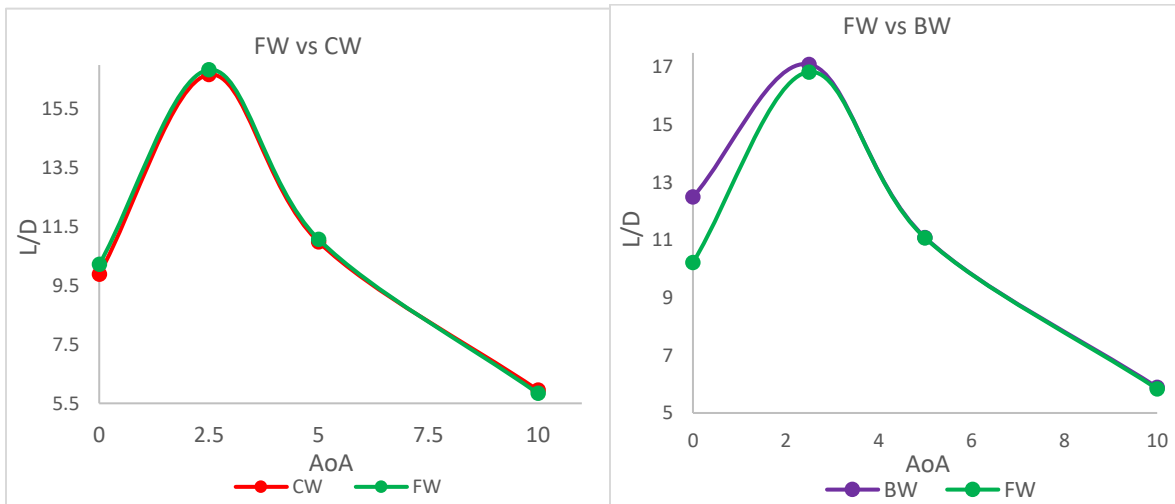


Figure 22 Comparison of L/D ratio of FW with CW and BW

Table 8 Percentage difference between FW and CW

AoA (°)	C _D (%)	C _L (%)	L/D (%)
2.5	-5.29	-4.38	0.99
5	-3.01	-2.25	0.79

Table 9 Percentage difference between FW and BW

AoA (°)	C _D (%)	C _L (%)	L/D (%)
2.5	-10.94	-12.32	-1.55
5	24.84	24.62	-0.18

Table 10 Percentage difference between BW and CW

AoA (°)	C _D (%)	C _L (%)	L/D (%)
2.5	6.34	9.05	2.58
5	-22.31	-21.56	0.97

Table 8, Table 9 and Table 10 present the percentage increase or decrease in the drag coefficient, lift coefficient, and lift-to-drag ratio at angles of attack of 2.5° and 5°, respectively, to facilitate a clearer comparison of aerodynamic performance between the different configurations.

C. Pressure and Vortices Behaviour:

1. Vortex core

Figure 23, Figure 24 and Figure 25 presents the contours of velocity invariant Q for the CW, BW and FW configurations at the same operating condition.

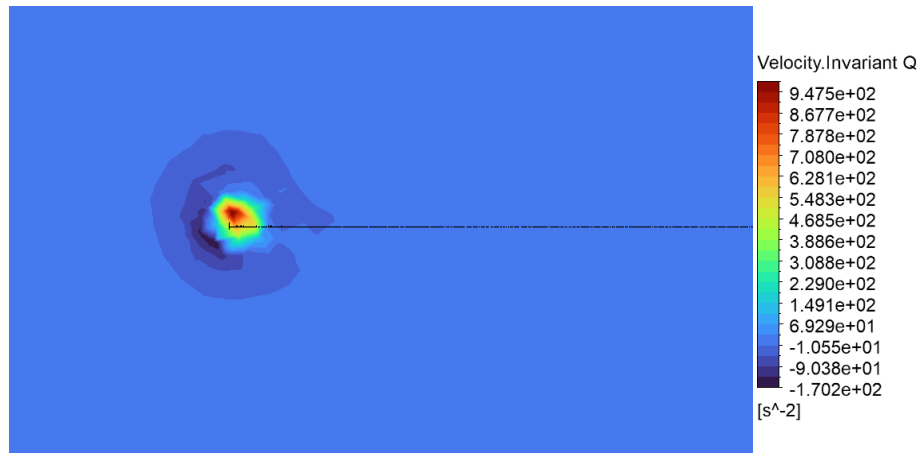


Figure 23 CW Q criterion

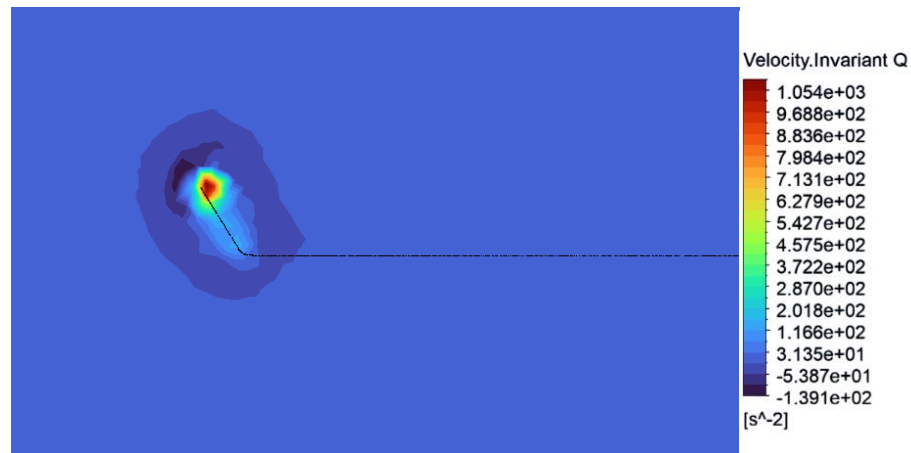


Figure 24 BW Q criterion

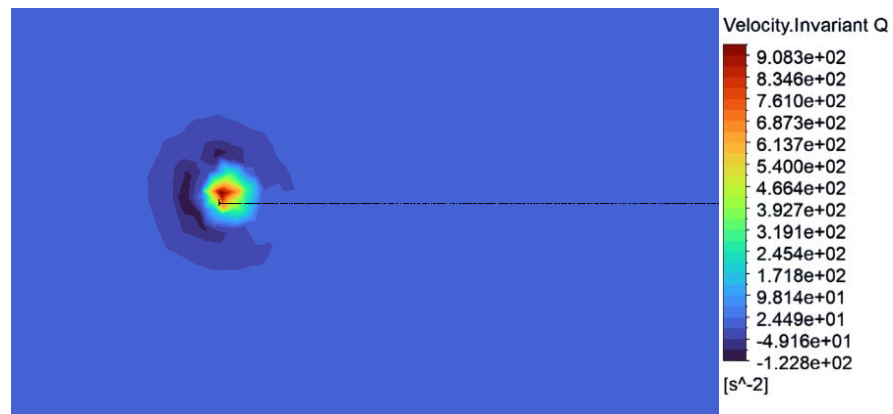


Figure 25 FW Q criterion

The clean wing exhibits a strong and compact vortex core, characterised by a high peak Q-value near the wingtip. This indicates a well-defined and energetic tip vortex, typically associated with increased induced drag.

For the blended winglet, the vortex core remains clearly identifiable but is slightly more diffused than that of the clean wing. Although the winglet modifies the vortex structure and redistributes its strength, a pronounced region of high Q-value persists downstream of the wingtip, indicating a coherent vortex.

In contrast, the fluidic winglet shows a marked reduction in vortex strength. The peak Q-values at the vortex core are lower than those of both the clean wing and the blended winglet, and the vortex structure appears more dispersed within the surrounding flow. This suggests that jet injection disrupts the formation of a concentrated vortex core and promotes earlier diffusion of rotational flow.

These findings demonstrate that the fluidic winglet is more effective in weakening the wingtip vortex than the blended winglet. The reduced magnitude and increased diffusion of the vortex core imply a decrease in induced drag and highlight the potential of fluidic injection as an alternative wingtip flow control strategy.

2. Vortex Strength

Figure 26, Figure 27 and Figure 28 presents the contours of the streamwise vorticity component (Velocity Curl X) for the CW, BW and FW configurations, to examine the cross-sectional structure and strength of the trailing vortex.

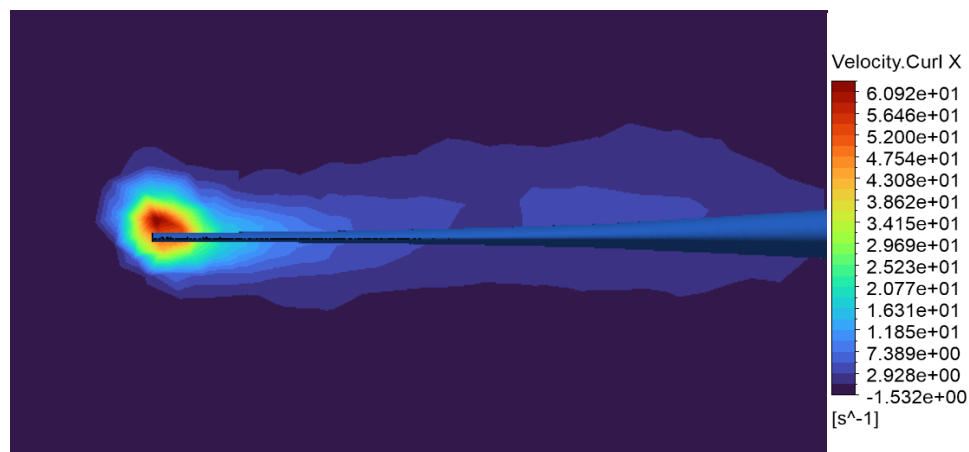


Figure 26 CW velocity curl x

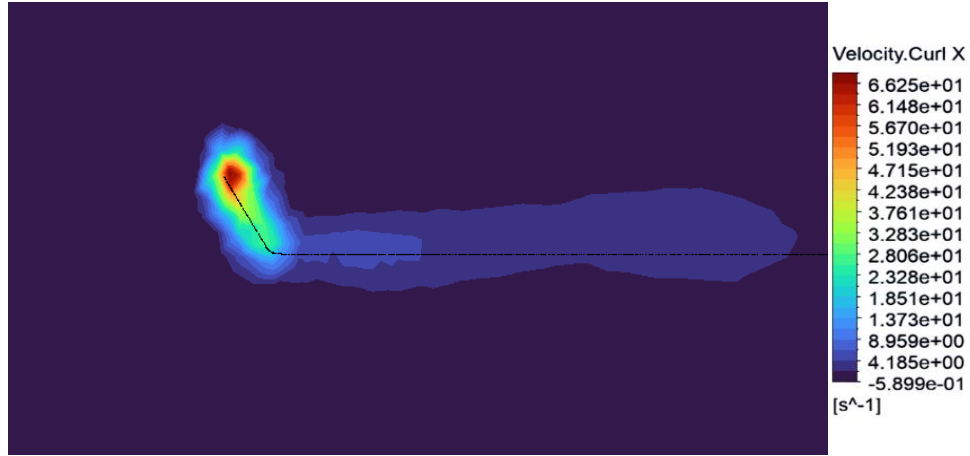


Figure 27 BW velocity curl x

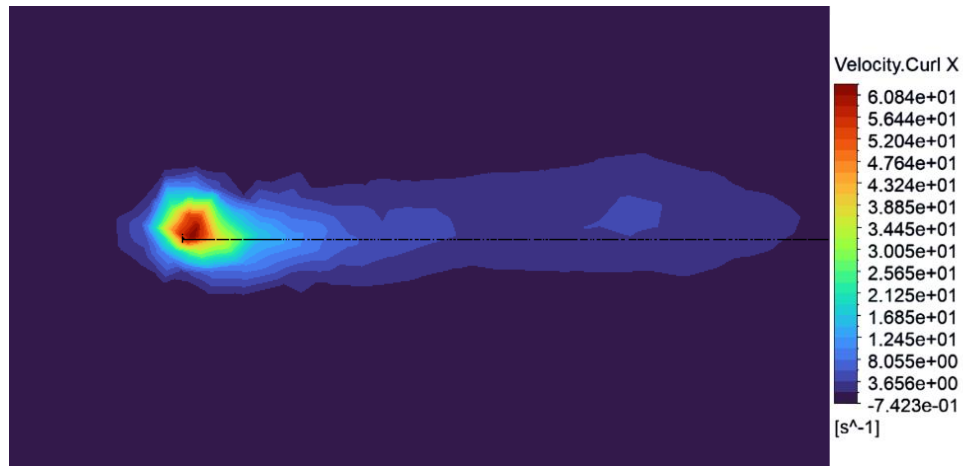


Figure 28 FW velocity curl x

The CW case exhibits a strong and compact vortex core with high curl magnitude, indicating a coherent and persistent vortex structure. For the BW configuration, the vortex core is displaced and moderately weakened, with a slight reduction in peak curl values and increased spatial spread, suggesting partial alteration of the vortex trajectory and strength.

In contrast, the FW configuration shows a more diffuse vortex pattern with a reduced and less concentrated region of high curl magnitude. The vortex core is less distinct than in both the CW and BW cases, indicating enhanced disruption and dissipation of the trailing vortex due to jet injection at the wingtip. These results show that, while the blended winglet provides passive mitigation of the wingtip vortex, the fluidic winglet achieves additional weakening through active flow control in the wake region.

3. Pressure at wake region

Figure 29, Figure 30 and Figure 31 Figure 28 presents the pressure contours in the wingtip wake region for the CW, BW and FW configurations, to examine the cross-sectional structure and strength of the trailing vortex

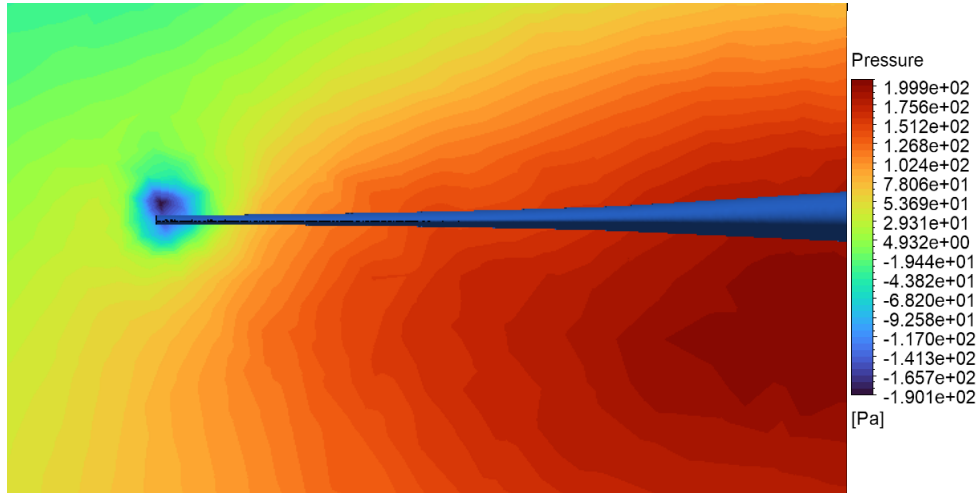


Figure 29 CW wake pressure

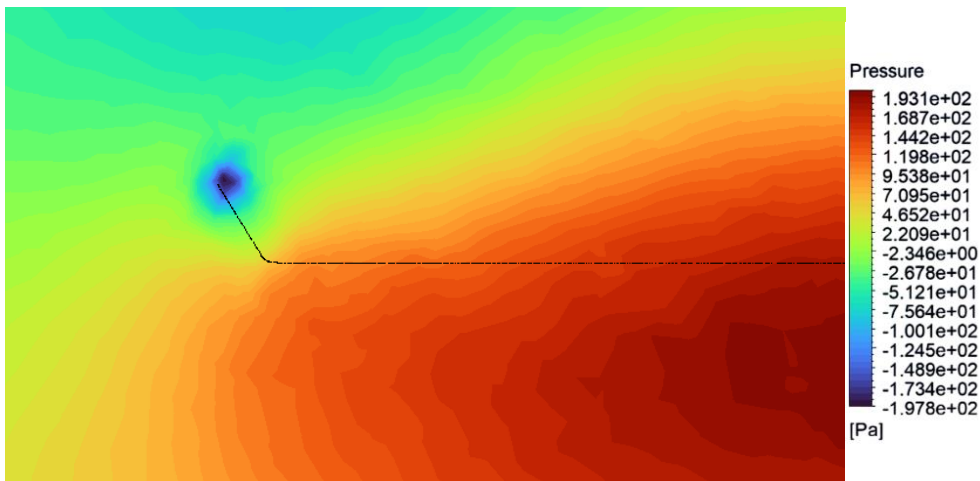


Figure 30 BW wake pressure

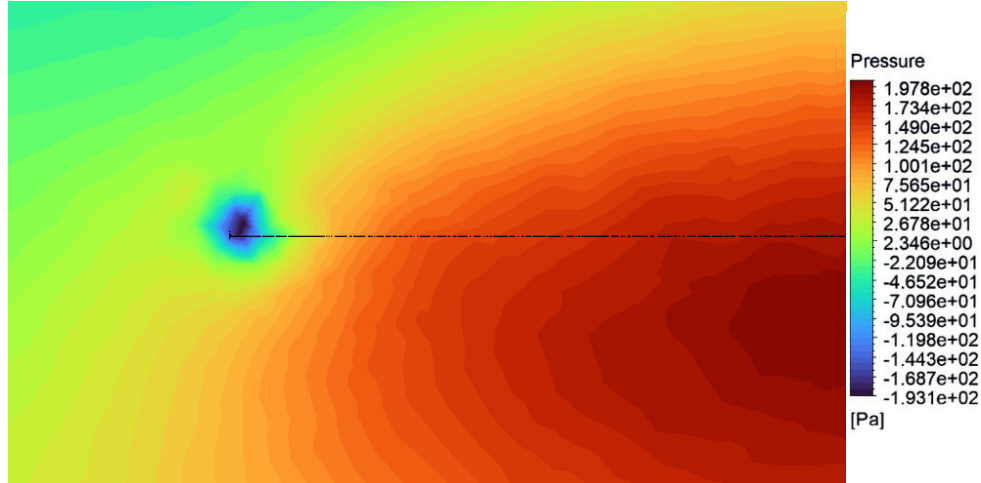


Figure 31 FW wake pressure

For the CW, a strong low-pressure core is present immediately downstream of the wingtip, indicating the formation of an intense and concentrated wingtip vortex. In the BW case, the low-pressure region is reduced in magnitude and becomes more spread out, showing partial weakening of the vortex due to the modified pressure field near the tip.

The FW exhibits the weakest and most diffused low-pressure region among the three configurations. The pressure contours are more uniform and less concentrated, indicating that the injected jet disrupts vortex formation and promotes faster pressure recovery in the wake.

Overall, the results show that the FW provides the greatest reduction in the pressure deficit associated with the wingtip vortex, suggesting improved vortex diffusion and a potential reduction in induced drag compared with both the CW and BW configurations.

D. Power Required and Fuel Consumption

The coefficient of jet momentum was calculated for each slot configuration and jet velocity in order to assess the practicality of the power required to generate the prescribed jet flow. The resulting values of the jet momentum coefficient for all configurations are listed in Table 11.

Table 11 Jet moment coefficient for different slot geometries at varying V_r

Slot geometry	V_r	C_μ
Cir_10	1.05	0.000039
	1.15	0.000047
	1.25	0.000055
Cir_20	1.05	0.000156

	1.15	0.000187
	1.25	0.000221
Cir_30	1.05	0.000350
	1.15	0.000420
	1.25	0.000496
Ob_900_20	1.05	0.000648
	1.15	0.000778
	1.25	0.000919
Ob_1000_20	1.05	0.000719
	1.15	0.000862
	1.25	0.001019
Ob_900_25	1.05	0.000814
	1.15	0.000976
	1.25	0.001153
Ob_1100_25	1.05	0.000991
	1.15	0.001188
	1.25	0.001404

Previous studies on fluidic control and circulation-control wings have shown that practical values of jet momentum coefficient typically lie in the range of approximately 3×10^{-4} to 7×10^{-4} , while values exceeding 1.0×10^{-3} are considered unrealistic for aircraft applications due to excessive power requirements. Such high jet momentum levels would require large pneumatic or compressor systems, resulting in unacceptable weight and fuel penalties [4,18].

Based on these considerations, a maximum jet momentum coefficient of 9×10^{-4} was adopted in the present study as the practical upper limit. Configurations producing values above this threshold were examined only to assess their aerodynamic feasibility under specific parametric conditions and were not considered viable for implementation on a commercial aircraft wing.

1. Power requirement

The power required by a fluidic winglet system is governed primarily by the mass flow rate and exit velocity of the injected jet. This requirement was estimated using the jet kinetic energy rate, expressed as,

$$P_j = \frac{\dot{m}_j V_j^2}{2\eta} \quad 2$$

Where P_j is the jet power, $\dot{m}_j$ is the jet mass flow rate, V_j is the jet exit velocity, and η represents the overall system efficiency. As the detailed architecture of the injection system has not been defined in this study, the system efficiency

could not be quantified. Therefore, for the purpose of estimation, the above equation was simplified by assuming an ideal system with no losses ($\eta=1$). Substituting the mass flow rate expression in equation 2 gives,

$$P_j = J \frac{\rho A_s V_j^3}{2} \quad 3[18]$$

In the present analysis, J was taken as unity due to the uncertainty associated with the system architecture and the absence of a defined compressor or bleed-air configuration [18].

Using this formulation, the estimated power required by the fluidic jet injection system for the selected operating condition was approximately 123 kW, which is about 0.3% of the total power generated by the Boeing 737-800 engine [21].

2. Range and fuel consumption

The performance of the FW was decided to be estimated based on the range and fuel consumption estimation method as suggested in [18]. To do that the drag polars were first estimated using the parabolic curve trendline and the relation 4 for both FW and BW configuration.

$$C_D = C_{D_0} + KC_L^2 \quad 4$$

Equations 5 and 6 represent the drag polar equations, approximated for the whole aircraft by dividing the drag polar equation (Figure 38 and Figure 39) of the wing by 30% as the wing makes up 30% of the total drag on aircraft [4,18].

For FW,

$$C_D = 0.005667 + 0.1611C_L^2 \quad 5$$

And for BW,

$$C_D = 0.00234 + 0.1337C_L^2 \quad 6$$

The range is estimated by using Breguet range equation given below,

$$R = \frac{V_\infty}{c} \times \frac{C_L}{C_D} \ln \omega \quad 7[22]$$

The consequent fuel consumed was approximated estimated by using fuel weight ratio relation at a range of 1525km for both FW and BW, it is given by,

$$\omega = \frac{1}{1 - u^2 \left[\frac{Rgc}{2V_{md}E_{max}u} \right]} \quad 8[4]$$

The estimated range for FW and BW are listed in Table 12.

Table 12 Range

FW Range (km)	BW Range (km)	Range difference (%)
1350	1700	-20

The estimated fuel weight ratio for FW and BW and the percentage of increase in the fuel consumption is presented in Table 13.

Table 13 Fuel weight ratio

FW ω	BW ω	Percentage difference (%)
1.263	1.1	14

The results show that the achievable range with the FW is about 20% lower than that of the BW, while fuel consumption increases by approximately 14%. This demonstrates that, although fluidic injection provides local flow control benefits, the additional power required for jet generation introduces a significant penalty at the aircraft level. As a result, the reduction in drag is outweighed by the energy cost of the injection system. The FW therefore does not provide a net performance benefit over the BW for cruise operation and leads to reduced mission efficiency in terms of both range and fuel usage.

IX. Conclusion

This study numerically investigated the performance of a fluidic winglet (FW) applied to a Boeing 737-800 wing at cruise conditions. Different slot geometries and jet parameters were analysed and compared with a clean wing (CW) and a blended winglet (BW). Among the configurations tested, the obround slot achieved the highest lift-to-drag ratio and was selected as the most effective FW design within the investigated range.

The results show that the FW improves aerodynamic performance relative to the CW at an angle of attack of 2.5°, mainly through drag reduction. However, the FW did not achieve a higher lift-to-drag ratio than the BW for a medium

aspect ratio wing. Although the FW reduced drag and modified the wake, its overall efficiency remained lower than that of the blended winglet.

This difference arises from the distinct operating principles of the two concepts. The BW improves performance by increasing the effective span through a passive geometric modification, whereas the FW relies on active jet injection to influence the local flow. While injection can reduce drag, it does not provide the same span-efficiency benefit as a physical winglet, resulting in a smaller improvement in lift-to-drag ratio. Similar trends have been reported in previous numerical and feasibility studies.

When system integration is considered, the limitations of the FW become more pronounced. Fluidic injection requires additional hardware such as compressors, ducting, or bleed-air supply, introducing extra mass and power demand. These lead to fuel and weight penalties that must be offset by aerodynamic gains. Since the FW does not outperform the BW in lift-to-drag ratio, such penalties result in an overall performance disadvantage. Therefore, the use of a fluidic winglet solely for moderate drag reduction is not justified when a blended winglet already provides superior efficiency without active energy input.

The FW simulations were performed using a medium-resolution mesh, and a dedicated mesh independence study was not conducted. Although finer meshes may improve the resolution of jet-flow interaction, it is unlikely that this would change the main conclusion that the FW remains less effective than the BW in terms of lift-to-drag ratio improvement for medium aspect ratio aircraft such as the Boeing 737-800.

Overall, this study shows that fluidic winglets can improve performance compared with a clean wing, but they do not exceed the effectiveness of conventional blended winglets and are further limited by system-level penalties. Their application is therefore more suitable for specialised or future aircraft concepts with integrated active flow control, rather than as a replacement for conventional winglets on current commercial transport aircraft.

Appendix

A. Mesh quality graphs:

Orthogonal quality:

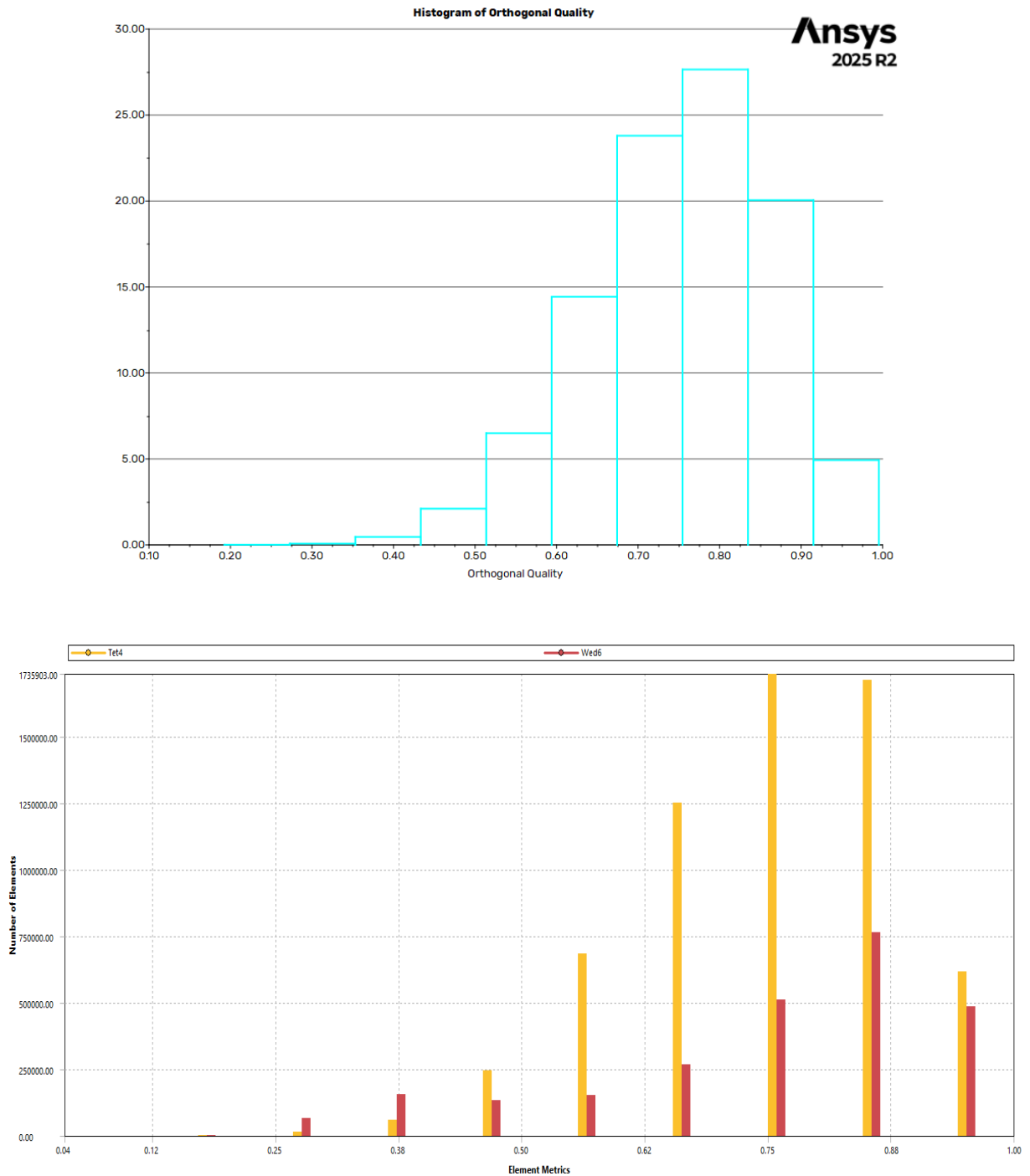


Figure 32 Orthogonal quality of CW mesh

Aspect ratio:

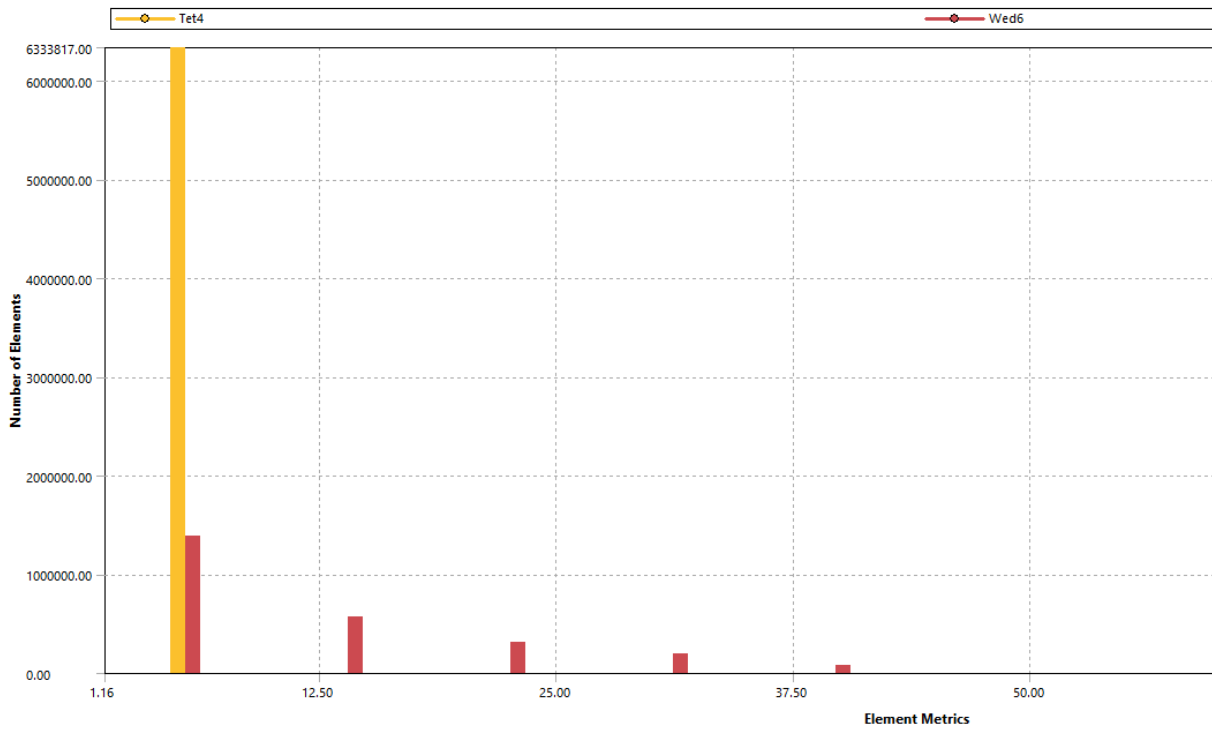


Figure 33 Aspect ratio of CW

Skewness:

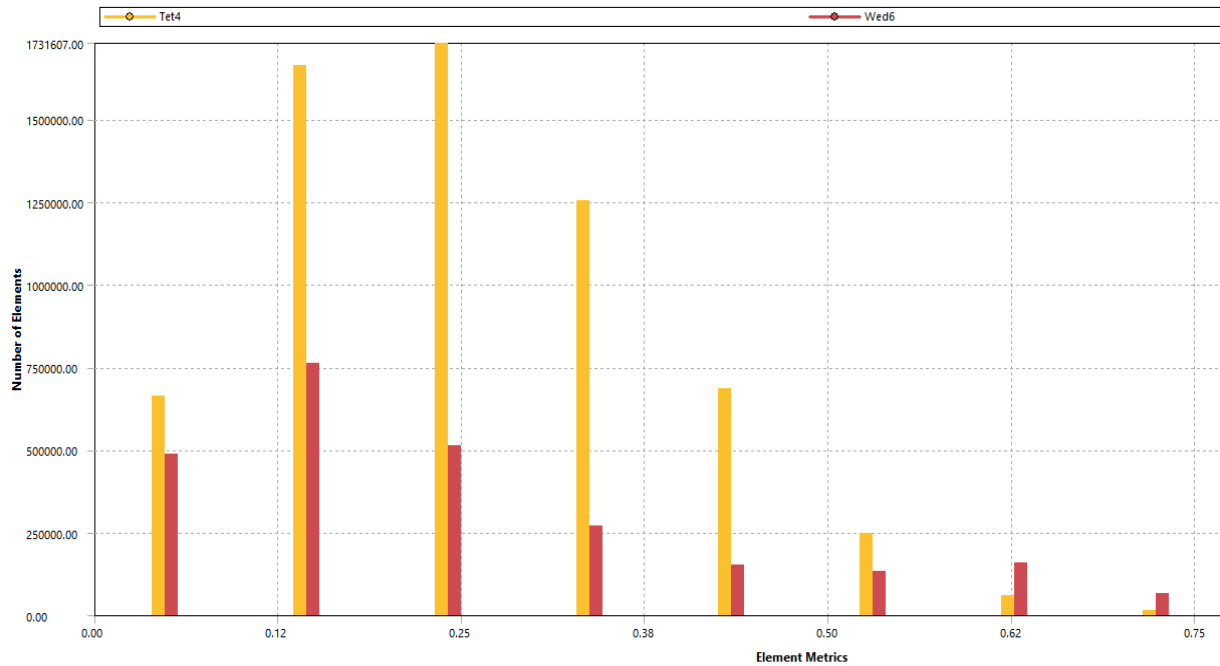


Figure 34 Skewness of CW

B. Boundary layer thickness

$$y = \frac{y^+ v}{u_\tau} \quad 9$$

Where,

y = first layer thickness (m)

y^+ = target non-dimensional wall distance

v = kinematic viscosity (m²/s)

u_τ = friction velocity (m/s)

C. Jet momentum coefficient

$$C_\mu = \frac{\dot{m}_j V_j}{1/2 \rho_\infty V_\infty^2 S_{ref}} \quad 10$$

Where, $\dot{m}_j = \rho_j A_s V_j$ and $\rho_j = \rho_\infty$

$$V_r = \frac{V_j}{V_\infty} \quad 11$$

D. Parametric analysis of other cases

Slot	AoA (°)	Velocity Ratio (V_r)	Jet Sweep Angle ϕ (°)	Jet Dihedral Angle δ (°)	C_D	C_L	L/D
cir_10	5	1.15	0	0	0.065896	0.728900	11.061369
	5	1.05	0	0	0.065898	0.728930	11.061489
	5	1.25	0	0	0.065897	0.728910	11.061353
cir_20	2.5	1.05	45	0	0.026575	0.446790	16.812418
	2.5	1.25	45	0	0.026575	0.446730	16.810160
	5	1.15	0	0	0.065912	0.729266	11.064270
	5	1.15	45	0	0.065908	0.729140	11.062997
	5	1.05	0	0	0.065914	0.729280	11.064114
	5	1.25	0	0	0.065912	0.729269	11.064259
	5	1.25	45	0	0.065910	0.729140	11.062661
	2.5	1.15	45	0	0.026585	0.446550	16.797066

	2.5	1.25	45	0	0.026581	0.446459	16.796141
	2.5	1.15	45	5	0.026581	0.446465	16.796256
	5	1.15	45	0	0.065829	0.727890	11.057285
ob_900;20	5	1.15	0	0	0.065839	0.728580	11.066085
	5	1.05	0	0	0.065830	0.728510	11.066535
ob_1000;20	5	1.15	0	0	0.065938	0.729560	11.064333
ob_900;25	2.5	1.15	45	0	0.026576	0.445800	16.774533
	2.5	1	0	0	0.026429	0.445040	16.839078
	2.5	0.95	0	0	0.026429	0.445040	16.839078
	5	1.15	0	0	0.065573	0.726255	11.075551
ob_1100;25	2.5	1.15	45	0	0.026565	0.446140	16.794278
	5	1.15	0	0	0.066017	0.730182	11.060597

E. Pressure contours at the symmetry plane

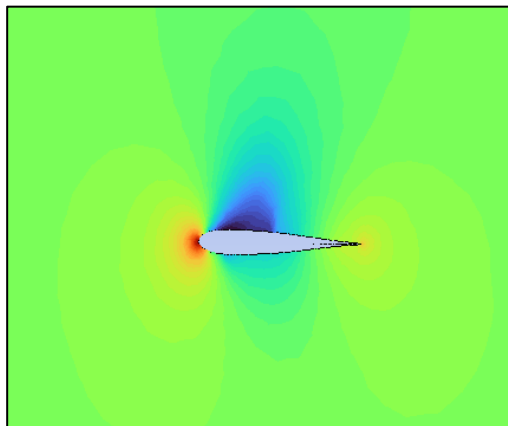


Figure 35 CW

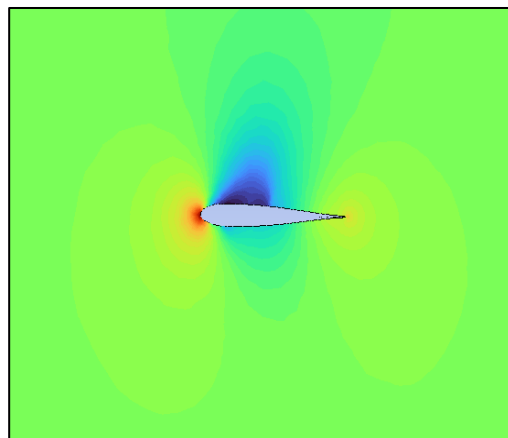


Figure 36 BW

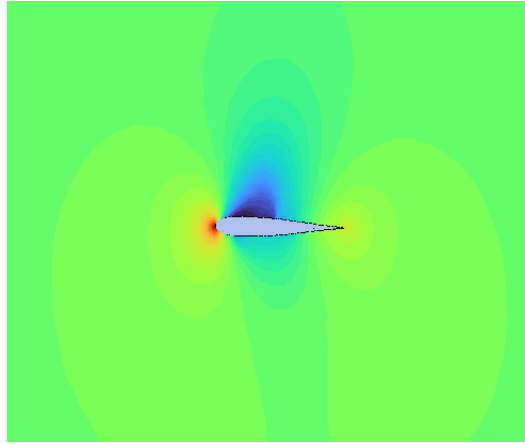


Figure 37 FW

F. Range and Fuel Estimation

The assumptions and values considered from literature and publicly available sources are listed below:

- $m_i = 79016 \text{ kg}$ [10]
- $L = W_i = m_i g$
- $\omega = 1.25$ [4]
- $\text{TSFC} = 0.0357 \text{ kg/KN}$ [10]
- $c = c_{mg} = 3.5 \times 10^{-4} \text{ s}^{-1}$

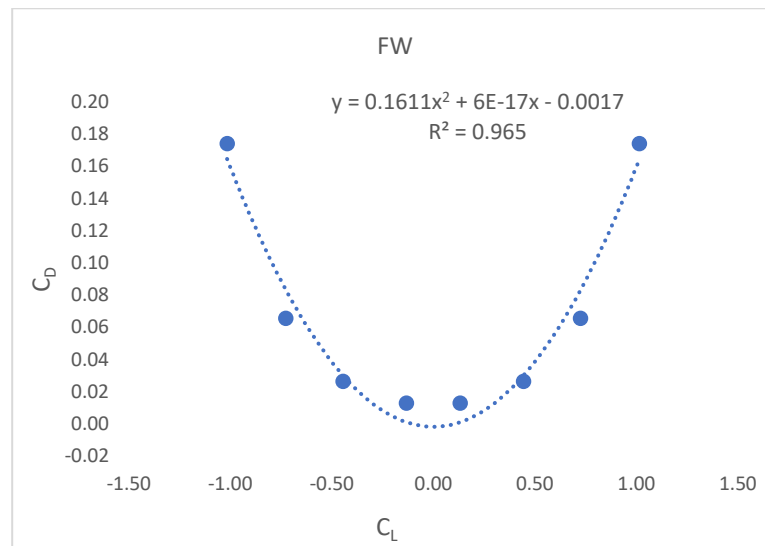


Figure 38 Drag polar of FW

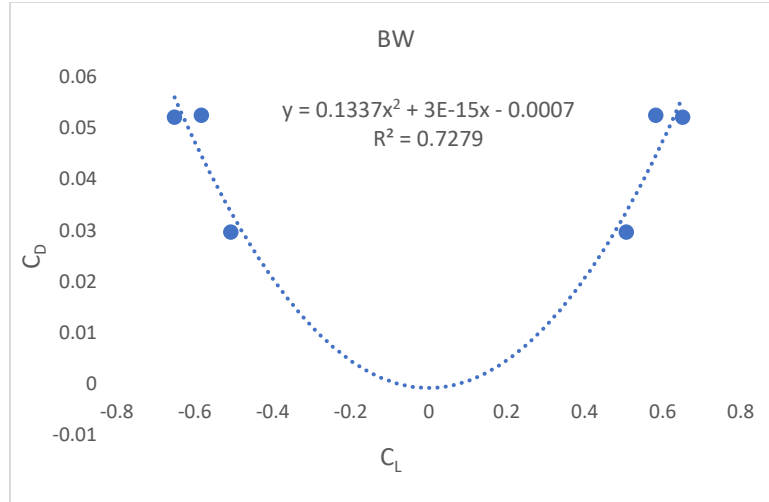


Figure 39 Drag polar of BW

Alternative range relation is given by Equation 12,

$$R = \frac{1}{g} \left[\frac{V_{md} E_{max}}{c} \right] 2u \left[\tan^{-1} \left(\frac{1}{u^2} \right) - \tan^{-1} \left(\frac{1}{\omega u^2} \right) \right] \quad 12$$

$$V_{md} = \sqrt{\frac{L}{0.5\rho S \sqrt{\frac{C_{D_0}}{K}}}} \quad 13$$

$$E_{max} = \frac{1}{2\sqrt{K C_{D_0}}} \quad 14$$

$$u = \frac{V_{\infty}}{V_{md}} \quad 15$$

The estimated V_{md} , E_{max} and u values for FW and BW are listed in Table 14.

Table 14

Wing Configuration	V_{md} (m/s)	E_{max}	u
FW	418.0425	16.548	0.55018
BW	497.75	28.268	0.46208

G. CURES form



8 January 2026

Dear Ms Sridhar ,

Reference: CURES/26942/2026

Project ID: 30409

Title: Determination of the feasibility of fluidic winglet over 737-800 blended winglet

We are pleased to inform you that you have successfully declared that your research project is a **Literature Review – based solely on openly available literature which is in the public domain, and you are undertaking desk-based research not involving any other form of data or information.**

You have also confirmed that your project **does not meet** any of the literature review specified exceptions, listed both within the relevant section of the CURES form and below:

1) Your supervisor has requested that you apply for approval through CURES because:

- The journals or data are in a sensitive area (please discuss this with your supervisor)
- The project will be embargoed i.e. **will not be publicly available via the Cranfield library immediately or longer term**

2) Approval is/will be specifically required by another external body e.g. journal publishers

Therefore, **you do not require ethical approval** and your CURES application will be automatically closed.

Please keep a copy of this letter safe, if this exception is in relation to your thesis project, you will need to include a copy with your final thesis submission.

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team

Acknowledgments

First and foremost, I would like to express my sincere gratitude to my supervisor, Dr Amir Zare Shahneh, for his invaluable guidance, encouragement, and continuous support throughout the course of this project. His expertise and constructive feedback have been instrumental in the completion of this work. I would also like to thank my colleagues, fellow students, and senior peers for their assistance, cooperation, and helpful discussions, which greatly contributed to the progress of this research. Finally, I wish to extend my deepest appreciation to my parents, sister, friends, and my pet for their unwavering support and constant encouragement throughout my studies. Their belief in my abilities, even from a distance, has been a continual source of motivation and inspiration, and has made this journey both possible and rewarding.

References

- [1] Chandra, D., and Misra, A., "Impact of Implementing Winglets on the Aerodynamic Performance of an Aircraft: A Review," *International Journal of Mechanical and Thermal Engineering*, Vol. 4, No. 1, 2023, pp. 44–54. <https://doi.org/10.22271/27078043.2023.v4.i1a.50>
- [2] Al-Khafaji, A. J., Panatov, G. S., and Boldyrev, A. S., "Using the Winglet Toe and Twist Angle to Improve Wing Aerodynamics Performance." <https://doi.org/10.21203/rs.3.rs-664368/v1>
- [3] LI JENNA, "Fluidic Wingtip," CRANFIELD UNIVERSITY, 2019.
- [4] Thimmarayappa, G., and Zare Shahneh, A., "Numerical Analysis of the Feasibility of Fluidic Winglets on a Moderate Aspect Ratio Wing," 2025.
- [5] Thimmegowda, H., Yadu Krishnan, S., Gisa, G. S., and Reddy, V. G., "Parametric Study of Fluid Injection Winglet on Aerodynamic Performance of the Wing," *Journal of Fluid Flow, Heat and Mass Transfer*, Vol. 9, 2022, pp. 23–30. <https://doi.org/10.11159/jffhmt.2022.003>
- [6] Almarzooqi, H., "Ejection Flow Direction Effect on the Fluidic Winglet: An Alternative to Conventional Winglet," 2024. <https://doi.org/10.2514/6.2024-4227>
- [7] Mandia, V., Sharma, V., Chandra, Y., Kumar, G., and Singh, R. K., "Optimizing Winglet Cant Angle for Enhanced Aircraft Wing Performance Using CFD Simulation and Hybrid ANN-GA," *International Journal for Numerical Methods in Fluids*, Vol. 97, No. 3, 2025, pp. 211–223. <https://doi.org/10.1002/fld.5341>
- [8] Widjaja William, S. A. Z., "Fluidic Winglet Optimisation for Drag Reduction In," *Aeronautics and Aerospace Open access Journal*, 2025. <https://doi.org/10.15406/aaaj.2025.09.00218>
- [9] Aristides Antonio, "Feasibility of Fluidic Winglet in Aircraft," Cranfield University, 2025.
- [10] Brady Chris, "Boeing 737 Detailed Technical Data," The Boeing 737 Technical Site (b737.org.uk).
- [11] "Boeing 737-800: Specs, Features, and Flight Experience," National Aero Stands, Aug 24 2025.
- [12] Bakhai, M. P., Mat, S. Bin, and Musa, N. A. B., "Aerodynamics of a Wing Body with Different Winglet Cant Angle," Vol. 477, 2024. <https://doi.org/10.1051/e3sconf/202447700029>
- [13] Selig, M. S., "UIUC Airfoil Coordinates Database," Department of Aeronautical and Astronautical Engineering, University of Illinois at Urbana-Champaign, 1996, [online database], URL: https://m.selig.ae.illinois.edu/ads/coord_database.html [retrived Jan. 3, 2026]
- [14] AirfoilTools, "Airfoil Database — AirfoilTools," AirfoilTools LLC, [online database], URL: <http://airfoiltools.com/search/list?page=b&no=0> [retrived Jan. 3, 2026]
- [15] Boeing, "3-View Drawings — Commercial Aircraft," The Boeing Company, Dec 06 2026.
- [16] Widjaja, W., and Zare Shahneh, A., "European Journal of Mechanics / B Fluids Feasibility of Hybrid Fluidic Winglet for Improving Aircraft Performance."

- [17] Mondal, A., Chatterjee, S., Tariang, A. M. D., Raj, L. P., and Debnath, K., “Numerical Investigation of On-Demand Fluidic Winglet Aerodynamic Performance and Turbulent Characterization of a Low Aspect Ratio Wing,” *Advances in Aircraft and Spacecraft Science*, Vol. 10, No. 2, 2023, pp. 107–125. <https://doi.org/10.12989/aas.2023.10.2.107>
- [18] D’SOUZA JASON ROQUE, “COMPUTATIONAL APPROACH TO INVESTIGATE FEASIBILITY OF A CONCEPTUAL FLUIDIC WINGLET,” CRANFIELD UNIVERSITY, 2018.
- [19] Widjaja, W., and Zare Shahneh, A., “European Journal of Mechanics / B Fluids Feasibility of Hybrid Fluidic Winglet for Improving Aircraft Performance.”
- [20] “ANSYS Fluent Convergence,” CFD LAND.
- [21] National Aero Stands, “Boeing 737-800: Specs, Features, and Flight Experience,” National Aero Stands, Jan 15 2026.
- [22] MIT OpenCourseWare, “Range and Endurance — Breguet Range Equation,” Massachusetts Institute of Technology, <https://web.mit.edu/16.unified/www/FALL/thermodynamics/notes/node98.html> [retrived Jan. 31, 2026]