

Numerical Investigation of Winglet Shape Effects on the Aerodynamic Performance of a Rectangular Wing

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ABSTRACT

This study investigates numerically the aerodynamic effects of ten winglet configurations mounted on a rectangular wing. Three-dimensional steady incompressible simulations are conducted using ANSYS Fluent package. Spalart-Allmaras turbulence model is used. Simulations are conducted at free-stream velocities of 10 m/s and 30 m/s. Angles of attack are examined from -7° to 15° . The simulated configurations are evaluated using the lift coefficient, drag coefficient, and lift-to-drag ratio. Results show that the blended winglet gives the highest and most consistent aerodynamic-efficiency improvement. The split-tip winglet achieves the maximum improvement of lift, but with a rapid increase in the associated drag. All winglet configurations produce higher drag than the baseline wing at positive angles of attack, while the plate winglet generally causes the largest drag penalties. Comparison of the obtained results with the published numerical data shows generally good agreement in the lift and drag coefficients, particularly at low and moderate angles of attack. The results demonstrate that the winglet selection should be based on their improvements in aerodynamic performance over a range of angles of attack and at different Reynolds numbers.

Keywords: Aerodynamic efficiency; Computational fluid dynamics; Winglet shapes, wingtip vortices.

دراسة عددية لتأثيرات شكل الجنيح الطرفي (Winglet) على الأداء الديناميكي الهوائي لجناح مستطيل

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ملخص البحث

تتناول هذه الدراسة -من خلال المحاكاة العددية- التأثيرات الديناميكية الهوائية لعشرة أشكال مختلفة من الجنيحات الطرفية المثبتة على جناح مستطيل. وقد أُجريت عمليات محاكاة ثلاثية الأبعاد لحالة التدفق المستقر وغير القابل للانضغاط باستخدام حزمة برمجيات ANSYS Fluent، مع الاعتماد على نموذج الاضطراب (Turbulence Model) من نوع Spalart-Allmaras. نُفذت المحاكاة عند سرعات تدفق حر تبلغ 10 م/ث و 30 م/ث، وشملت دراسة زوايا هجوم تتراوح بين -7° و 15° درجات و15 درجة. وجرى تقييم الأشكال المدروسة استناداً إلى معاملات الرفع والسحب ونسبة الرفع إلى السحب. وأظهرت النتائج أن الجنيح الطرفي المدمج (Blended Winglet) يحقق التحسن الأفضل والأكثر استقراراً في الكفاءة الديناميكية الهوائية.

في حين يحقق الجنيح الطرفي ذو الطرف المشقوق (**Split-tip Winglet**) أعلى تحسن في قوة الرفع، إلا أنه يتسبب في زيادة سريعة في قوة السحب المصاحبة. وتنتج جميع أشكال الجنيحات الطرفية قوة سحب أعلى مقارنة بالجنح الأساسي عند زوايا الهجوم الموجبة، حيث يتسبب الجنيح الطرفي المسطح (**Plate Winglet**) عموماً في أكبر قدر من الزيادة في السحب. كما أظهرت مقارنة النتائج المحصلة مع البيانات العددية المنشورة توافقاً جيداً بشكل عام فيما يخص معاملات الرفع والسحب، لا سيما عند زوايا الهجوم المنخفضة والمتوسطة. وتؤكد النتائج أن اختيار الجنيح الطرفي يجب أن يستند إلى مدى تحسينه للأداء الديناميكي الهوائي عبر نطاق من زوايا الهجوم وعند قيم مختلفة لأعداد رينولدز (**Reynolds numbers**).
الكلمات الدالة: الكفاءة الديناميكية الهوائية؛ ديناميكا الموائع الحسابية؛ أشكال الجنيحات الطرفية؛ دوامات أطراف الأجنحة.

1. Introduction

Finite wings generate wingtip vortices because of the pressure difference between their lower and upper surfaces. The associated spanwise flow and downwash contribute to induced drag and reduce aerodynamic efficiency, particularly under high-lift operating conditions [1]. Controlling wingtip flow is therefore an important objective in aerodynamic design. Winglets are passive devices used to modify wingtip-vortex development without requiring a substantial increase in wingspan [2]. Their performance depends on several factors, including geometry, cant angle, wing planform, angle of attack, and Reynolds number. Previous numerical and experimental studies have shown that blended, raked, split, spiroid, and multiple-winglet configurations can produce different effects on lift, drag, and lift-to-drag ratio [3–7]. These studies also indicate that a configuration providing high lift does not necessarily offer the highest aerodynamic efficiency over the entire operating range.

Most previous investigations considered a limited number of winglet geometries or focused on a single Reynolds number. Direct comparisons involving several airfoil-based and plate-type winglets mounted on the same rectangular wing remain limited. The present study addresses this gap by numerically comparing ten winglet configurations: raked, blended, split-tip, fence, full and half NACA 0012, plate, half plate, fence plate, and half fence plate.

Three-dimensional CFD simulations are conducted using ANSYS Fluent at free-stream velocities of 10 and 30 m/s, corresponding to Reynolds numbers of 1.23×10^5 and 3.69×10^5 , respectively. Angles of attack from -7° to 15° are investigated. The configurations are evaluated using the lift coefficient, drag coefficient, and lift-to-drag ratio, while grid independence, convergence monitoring, and comparison with published numerical data are used to assess the reliability of the numerical procedure. The main objective of this study is to determine how winglet geometry, angle of attack, and Reynolds number affect the aerodynamic performance of the rectangular wing.

2. Numerical Methodology

The numerical methodology used in this study is organized to evaluate the aerodynamic effects of different winglet configurations on the rectangular baseline wing.

2.1 Wing and Winglet Geometry

Wing and winglet geometries are developed in SolidWorks. The baseline configuration was a rectangular NACA 2415 semi-wing with a chord of 0.18 m, a semi-span of 0.45 m, and an aspect ratio of 5. The semi-wing was used in accordance with the symmetry boundary condition, as shown in Figure 1.

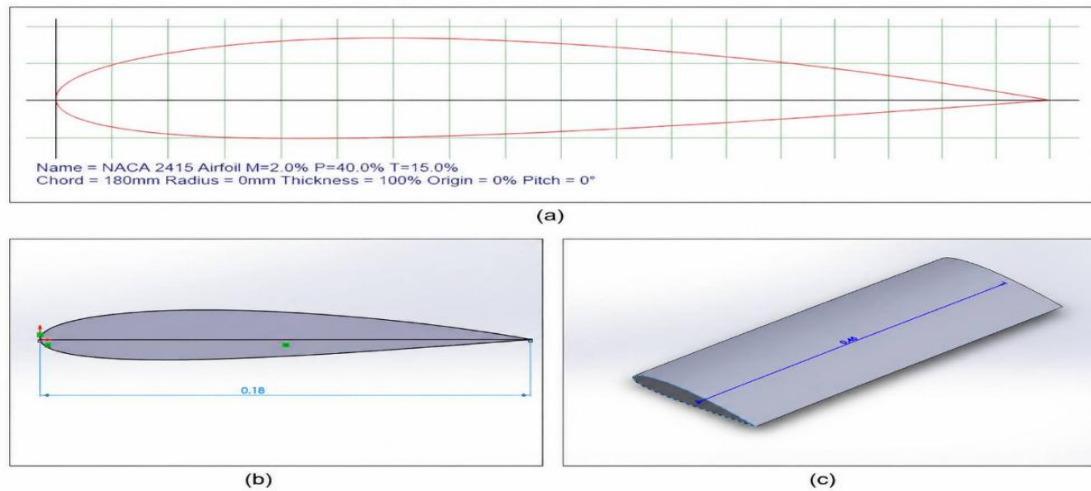


Figure 1. Geometry and principal dimensions of the rectangular baseline semi-wing based on the NACA 2415 airfoil: (a) NACA 2415 airfoil profile, (b) chord length, and (c) semi-span.

Ten winglet configurations are classified into three groups: NACA 2415-based, NACA 0012-based, and plate-type winglets. The NACA 2415 group includes raked, blended, split-tip, and fence winglets. The raked, blended, and split-tip configurations have a cant angle of 60° and a chord of 0.09 m, whereas the fence winglet has a cant angle of 90° and the same chord, as shown in Figure 2.

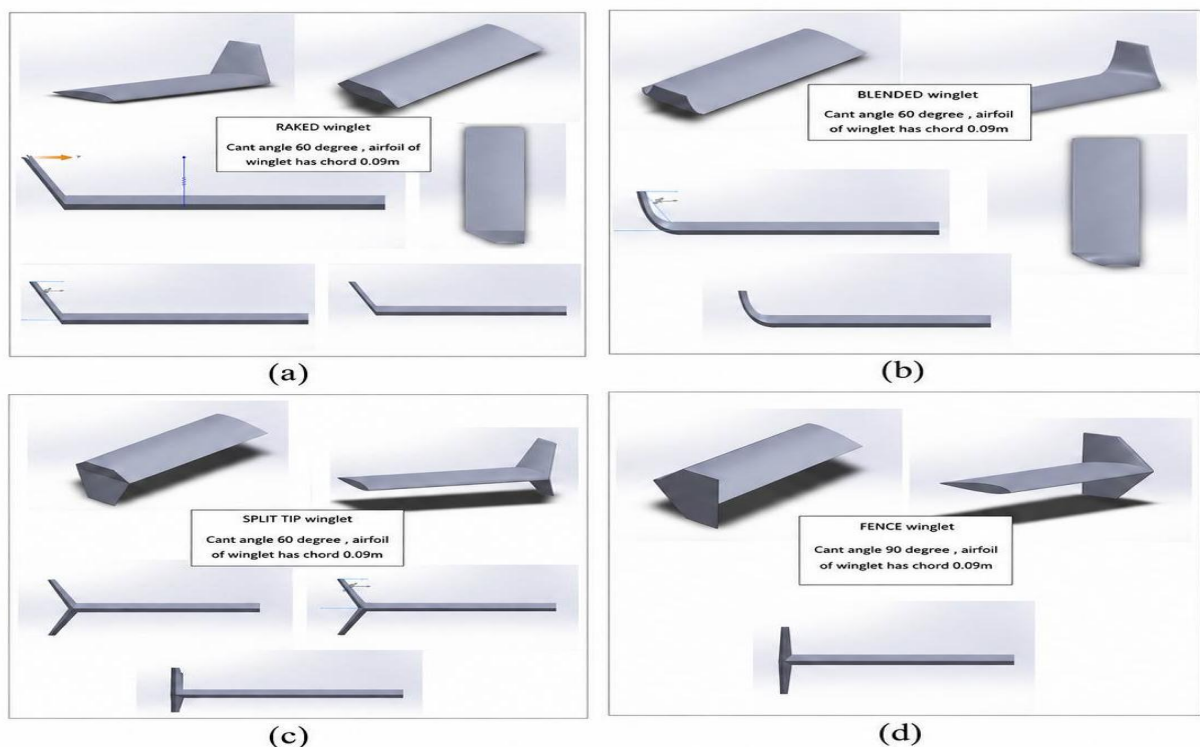


Figure 2. Geometrical views of the investigated NACA 2415-based winglet configurations: (a) raked winglet, (b) blended winglet, (c) split-tip winglet, and (d) fence winglet.

The full and half NACA 0012 winglets have a cant angle of 90° and a chord of 0.18 m. Their vertical extensions are 0.18 and 0.09 m, respectively, as shown in Figure 3.

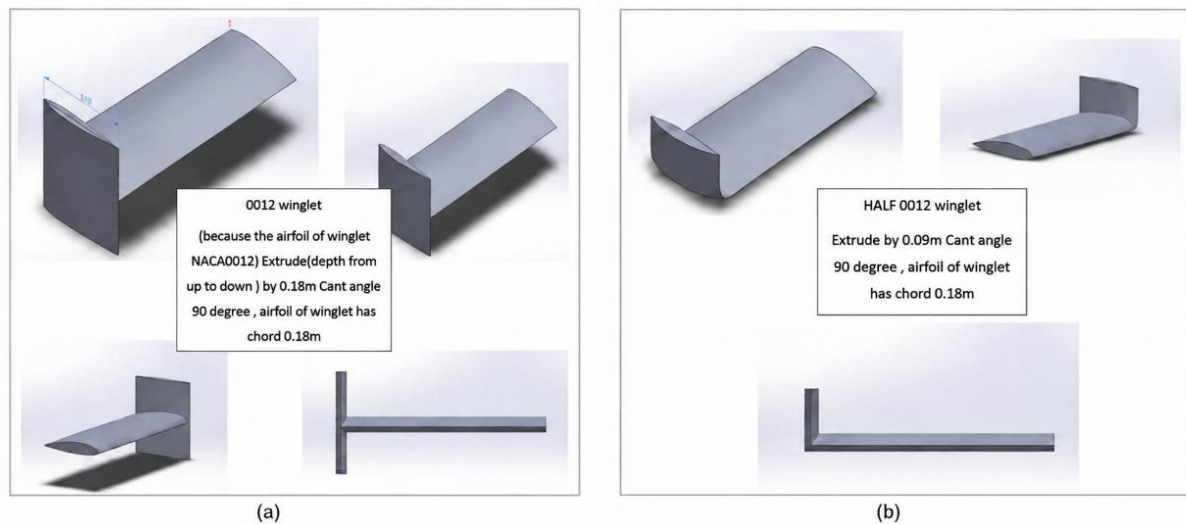


Figure 3. Geometrical views of the investigated NACA 0012-based winglet configurations: (a) full NACA 0012 winglet and (b) half NACA 0012 winglet.

The plate-type group comprises plate, half-plate, fence-plate, and half-fence-plate winglets. The full and half plates have approximate dimensions of 0.18×0.18 m and 0.18×0.09 m, respectively. The fence-plate has a side dimension of 0.18 m and upper and lower extensions of 0.09 m, whereas the half-fence-plate retained one 0.09×0.09 m extension. All plate-type configurations have an extrusion depth of 0.009 m, as shown in Figure 4. The completed models are then imported into ANSYS Workbench for computational-domain generation and CFD analysis.

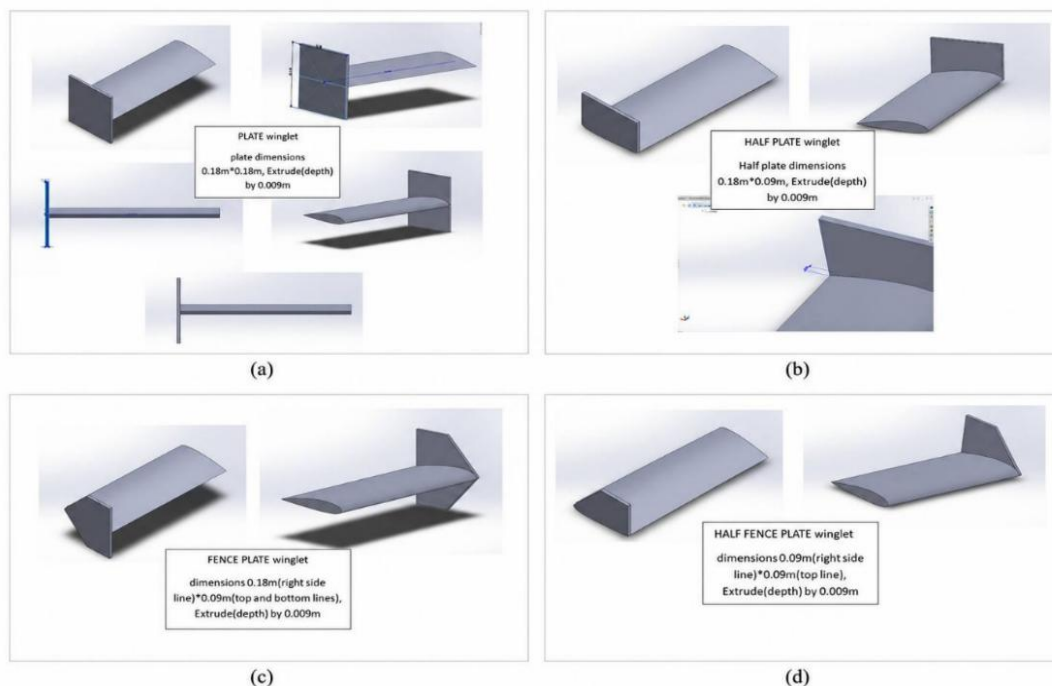


Figure 4. Geometrical views of the investigated plate-type winglet configurations: (a) plate winglet, (b) half plate winglet, (c) fence-plate winglet, and (d) half-fence-plate winglet.

2.2 Computational Domain and Mesh Generation

The baseline wing and winglet geometries are imported into ANSYS Design Modeler, where a three-dimensional C-type computational domain is constructed around each configuration. The domain

dimensions are $20c$ in length, $25c$ in width, and $11.11c$ in depth, where $c=0.18$ m is the wing chord. The corresponding dimensional values are $3.6 \text{ m} \times 4.5 \text{ m} \times 2.0 \text{ m}$, respectively. The fluid region is generated using enclosure and Boolean-subtraction operations, and the required angle of attack is assigned before mesh generation.

An unstructured tetrahedral mesh is generated with refinement near the wing and winglet surfaces and progressively larger elements toward the outer domain boundaries. Ten inflation layers are applied with a first-layer height of 0.001 m, a growth rate of 1.1 , medium smoothing, and a reported near-wall value of $Y^+=36$.

The principal computational-domain dimensions and mesh-generation parameters are given in Table 1.

Table 1. Computational-domain dimensions and mesh-generation parameters.

Parameter	Value
Computational-domain type	Three-dimensional C-type domain
Wing chord	0.18 m
Domain length	$20c$ (3.6 m)
Domain width	$25c$ (4.5 m)
Domain depth	$11.11c$ (2 m)
Mesh type	Unstructured tetrahedral
Near-wall treatment	Inflation layers
Number of inflation layers	10
First-layer height	0.001 m
Growth rate	1.1
Smoothing	Medium
Y^+	36
Selected element range at 30 m/s	Approximately $700,000$ – $870,000$
Selected element range at 10 m/s	Approximately $500,000$ – $800,000$

Because of the different geometrical complexities of the investigated configurations, the global element size of the outer computational domain was adjusted for each case. The values reported in Table 2 refer to the global C-domain element size and do not represent the local mesh size adjacent to the wing and winglet surfaces. Local refinement was applied around the aerodynamic surfaces, together with the inflation layers described above, while progressively larger elements were used toward the outer domain boundaries. The adopted values are listed in Table 2.

Table 2. Global outer-domain element sizes adopted for the baseline wing and investigated winglet configurations at 30 and 10 m/s.

Configuration	Global outer-domain element size at 30 m/s (m)	Global outer-domain element size at 10 m/s (m)
Baseline wing	0.20	0.35
Raked winglet	0.35	0.45
Blended winglet	0.30	0.35
Split-tip winglet	0.34	0.45
Fence winglet	0.34	0.40
NACA 0012 winglet	0.32	0.40
Half NACA 0012 winglet	0.29	0.30
Plate winglet	0.25	0.35
Half plate winglet	0.25	0.30
Fence-plate winglet	0.25	0.29
Half-fence-plate winglet	0.27	0.30

A representative grid-independence assessment was performed for the baseline NACA 2415 wing at $\alpha = 10^\circ$, following the general approach adopted in the reference study [7]. The mesh was progressively refined, producing meshes ranging from 122,828 to 964,733 elements at 30 m/s and from 122,983 to 964,990 elements at 10 m/s. As shown in Figure 5, the lift coefficient approaches a nearly stable value as the mesh density increases. Accordingly, mesh ranges of approximately 700,000–870,000 elements at 30 m/s and 500,000–800,000 elements at 10 m/s were adopted for the subsequent simulations. The baseline wing was used as the representative reference case for mesh sensitivity, while local refinement and inflation layers were applied around the wing and winglet surfaces according to the geometrical characteristics of each configuration.

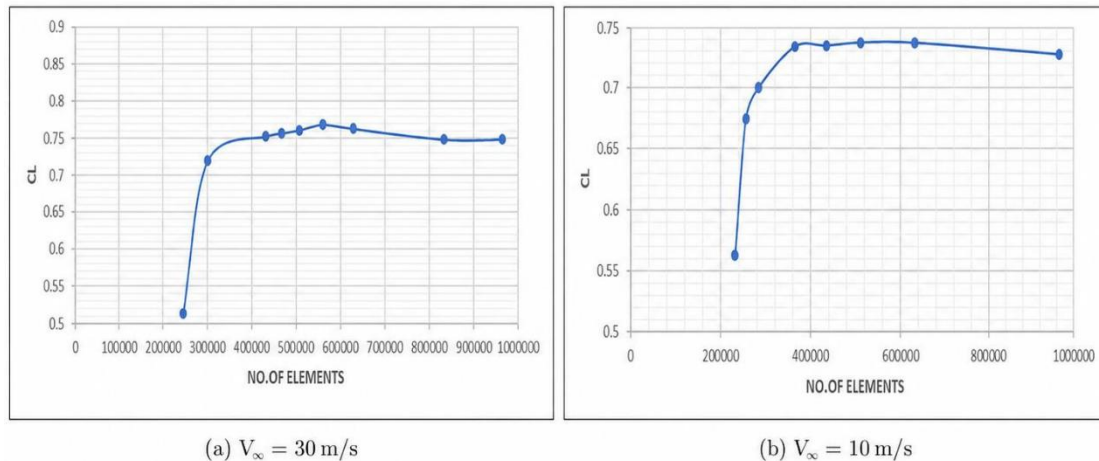


Figure 5. Grid-independence assessment based on the variation of the baseline-wing lift coefficient with mesh element number at $\alpha = 10^\circ$: (a) $V = 30$ m/s and (b) $V = 10$ m/s.

2.3 Numerical Solver and Boundary Conditions

Numerical simulations are performed using the three-dimensional, pressure-based, steady-state solver in ANSYS Fluent. Spalart–Allmaras turbulence model [8] is employed, with second-order discretization schemes applied to the pressure and momentum equations. Free-stream velocities of 10 and 30 m/s are investigated, corresponding to Reynolds numbers of 1.23×10^5 and 3.69×10^5 , respectively. The angles of attack range from -7° to 15° . The upstream boundary facing the free-stream flow is defined as a velocity inlet, while the downstream boundary opposite the inlet is defined as a pressure outlet with a pressure of 101325 Pa. The wing and winglet surfaces are treated as stationary no-slip walls. The upper, lower, and rear spanwise boundaries are defined as walls, whereas the front boundary is assigned as a symmetry plane. The applied boundary conditions are illustrated in Figure 6.

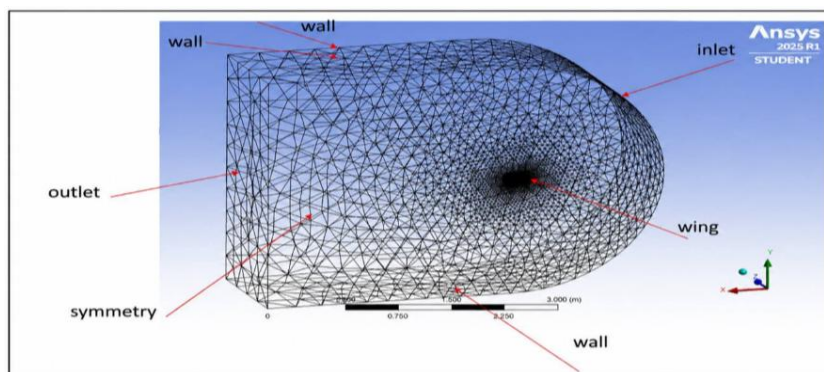


Figure 6. Boundary conditions applied to the C-type computational domain, including the velocity inlet, pressure outlet, wing and winglet no-slip walls, and the remaining domain boundaries.

Air properties, backflow turbulence settings, reference values, discretization schemes, and the complete boundary conditions are summarized in Table 3. A residual convergence criterion of 1×10^{-5} and a maximum of 1000 iterations are applied to each numerical case.

Table 3. Numerical solver settings and boundary conditions used in the CFD simulations.

Parameter	Setting / Value
CFD software	ANSYS Fluent
Solver formulation	Three-dimensional, pressure-based
Flow condition	Steady-state, subsonic flow
Turbulence model	Spalart–Allmaras, one equation
Working fluid	Air
Air density	1.225 kg/m^3
Dynamic viscosity	$1.7894 \times 10^{-5} \text{ kg/(m s)}$
Temperature	288.16 K
Free-stream velocities	10 and 30 m/s
Reynolds numbers	1.23×10^5 and 3.69×10^5
Angles of attack	$-7^\circ, -4^\circ, 0^\circ, 4^\circ, 7^\circ, 10^\circ, 12^\circ, 15^\circ$
Inlet boundary	Velocity inlet
Outlet boundary	Pressure outlet
Outlet pressure	101325 Pa
Wing and winglet surfaces	Stationary no-slip walls
Upper boundary	Wall
Lower boundary	Wall
Rear spanwise boundary	Wall
Front boundary	Symmetry
Backflow turbulence intensity	5%
Backflow turbulent viscosity ratio	10
Reference area	0.081 m^2
Reference length	0.18 m
Pressure discretization	Second order
Momentum discretization	Second order
Residual convergence criterion	1×10^{-5}
Number of iterations	1000

2.4 Convergence and Post-Processing

Numerical convergence is assessed by monitoring the residual histories together with the stability of the lift and drag coefficients. A solution is considered converged when the residuals satisfy the criterion of 1×10^{-5} reported in Table 3 and C_L and C_D become stable without significant oscillations. For the representative baseline semi-wing case at $V=30 \text{ m/s}$ and $\alpha=12^\circ$, the continuity residual decreases to approximately 10^{-6} , while C_L and C_D stabilize at 0.80247 and 0.088748, respectively.

After convergence, the lift coefficient, drag coefficient, and lift-to-drag ratio are extracted for each configuration. Velocity and static-pressure contours are also obtained to examine the flow-field characteristics. The aerodynamic results are subsequently compared using coefficient curves and percentage variations relative to the baseline wing.

3. Mathematical Equations

The aerodynamic performance is evaluated using the lift coefficient, drag coefficient, and lift-to-drag ratio. The lift and drag coefficients are calculated as:

$$C_L = \frac{L}{\frac{1}{2}\rho V^2 S} \quad (1)$$

$$C_D = \frac{D}{\frac{1}{2}\rho V^2 S} \quad (2)$$

and the aerodynamic efficiency is expressed as:

$$\frac{L}{D} = \frac{C_L}{C_D} \quad (3)$$

The Reynolds number is calculated using:

$$Re = \frac{\rho V c}{\mu} \quad (4)$$

where L and D are the lift and drag forces, ρ is the air density, V is the free-stream velocity, S is the reference area, c is the wing chord, and μ is the dynamic viscosity.

The percentage variation of each aerodynamic parameter relative to the baseline wing is calculated using:

$$\Delta X (\%) = \frac{X_w - X_b}{|X_b|} \times 100 \quad (5)$$

where X represents C_L , C_D , or C_L/C_D , while the subscripts w and b refer to the winglet configuration and baseline wing, respectively. For the drag coefficient, a positive value indicates increased drag, whereas a negative value indicates drag reduction.

4. Validation with Published Numerical Data

The baseline-wing C_L and C_D at $V=30$ m/s are compared with the numerical results of Abd and Ali [7] for a rectangular NACA 2415 wing with the same chord, span, and aspect ratio. The present and published Reynolds numbers are 3.69×10^5 and 3.72×10^5 , respectively. Figure 7 (a) shows similar trends in C_L up to 12° , with differences of 1.17%, 14.07%, 4.15%, 5.56%, and 0.31% at 0° , 4° , 7° , 10° , and 12° , respectively. At 15° , the C_L difference reaches 11.87%, likely due to differences in turbulence modeling, mesh density, and domain treatment. These percentages represent relative differences calculated with respect to the corresponding published C_L values. Therefore, although the absolute C_L difference is larger at 15° (0.10204) than at 4° (0.04783), the relative percentage difference is smaller at 15° .

For C_D , Figure 7(b) shows differences of 0.60%, 8.25%, 5.86%, 3.53%, 11.25%, and 5.67% at 0° , 4° , 7° , 10° , 12° , and 15° , respectively. Overall, the comparison of both C_L and C_D with the published numerical data supports the reliability of the present CFD model.

5. Results and Discussion

The results are presented through representative CFD contours followed by C_L , C_D , and C_L/C_D curves. Percentage variations are calculated relative to the baseline wing. The quantitative discussion focuses on $\alpha \geq 0^\circ$, while the complete angle-of-attack range is retained in the figures.

5.1 Flow-Field Characteristics

Figures 8 and 9 present the velocity and static-pressure contours of the baseline semi-wing at $V=30$ m/s. At $\alpha=10^\circ$, the relatively smooth flow and narrow wake indicate predominantly attached flow. At $\alpha = 12^\circ$, the wake becomes more disturbed, and signs of incipient flow separation begin to appear near the trailing edge of the upper surface. Correspondingly, C_L increased from 0.74947 to 0.80247, while C_D increased from 0.068494 to 0.088748. Because different contour scales were used, the comparison is qualitative.

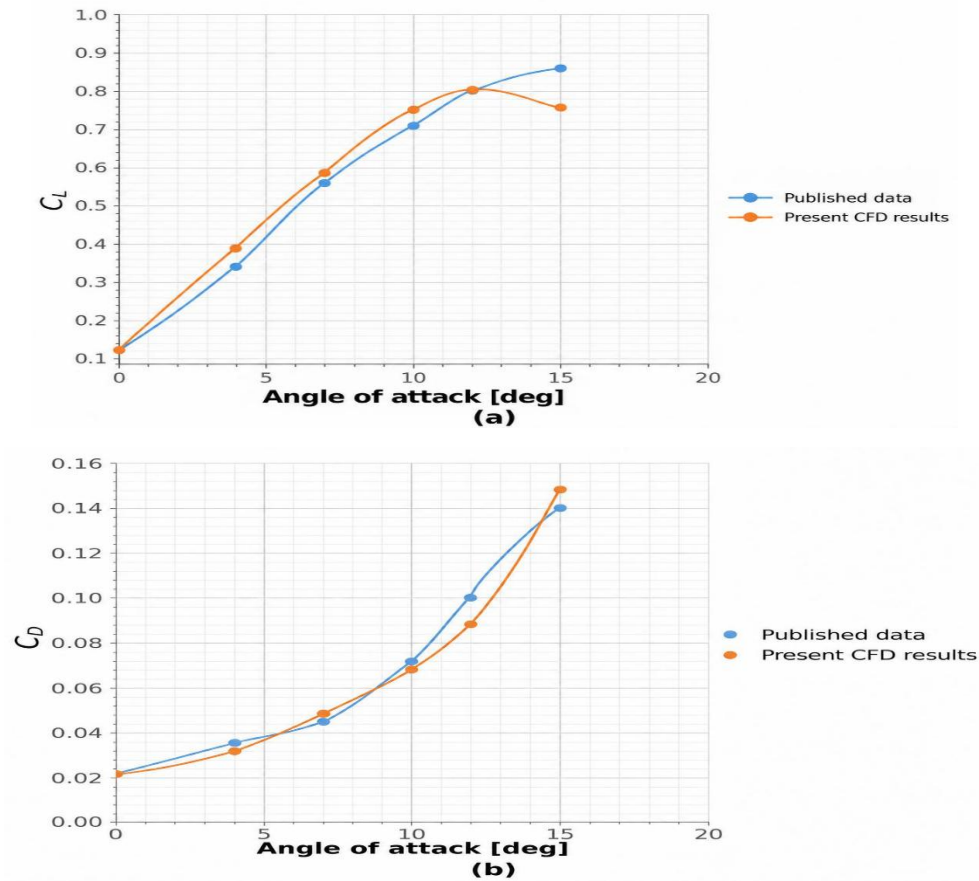


Figure 7. Comparison of the baseline-wing aerodynamic coefficients obtained in the present study with published numerical data reported by Abd and Ali [7] at $V=30$ m/s: (a) lift coefficient C_L , and (b) drag coefficient C_D .

The pressure distribution over the wing and winglet surfaces contributes to the aerodynamic forces acting on each configuration. Together with the viscous shear effects resolved by the CFD model, the resulting lift and drag forces were used in Eqs. (1) and (2) to calculate the lift and drag coefficients, C_L and C_D , respectively. Therefore, the pressure-field results provide qualitative insight into the aerodynamic loading, while the aerodynamic coefficients provide the quantitative performance assessment.

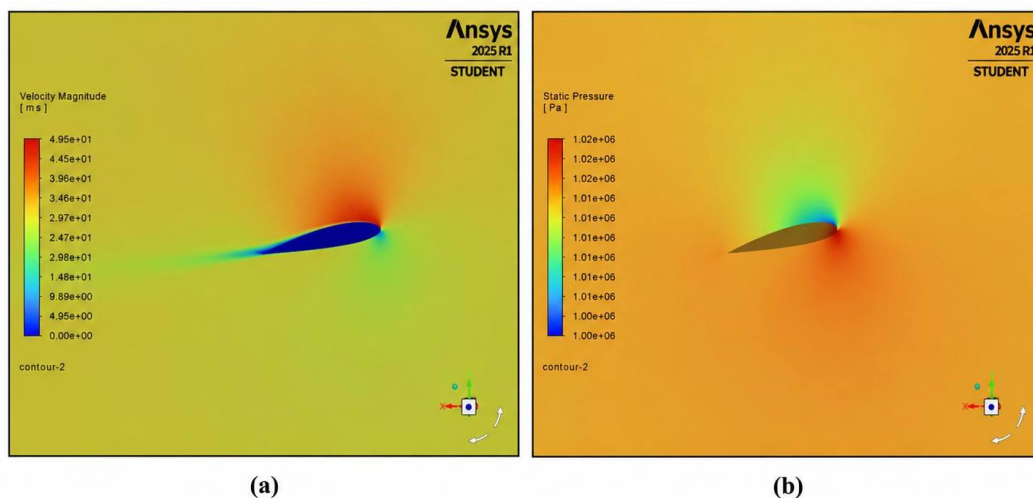


Figure 8. Velocity and static-pressure distributions around the baseline semi-wing at $V=30$ m/s and $\alpha=10^\circ$: (a) velocity magnitude and (b) static pressure.

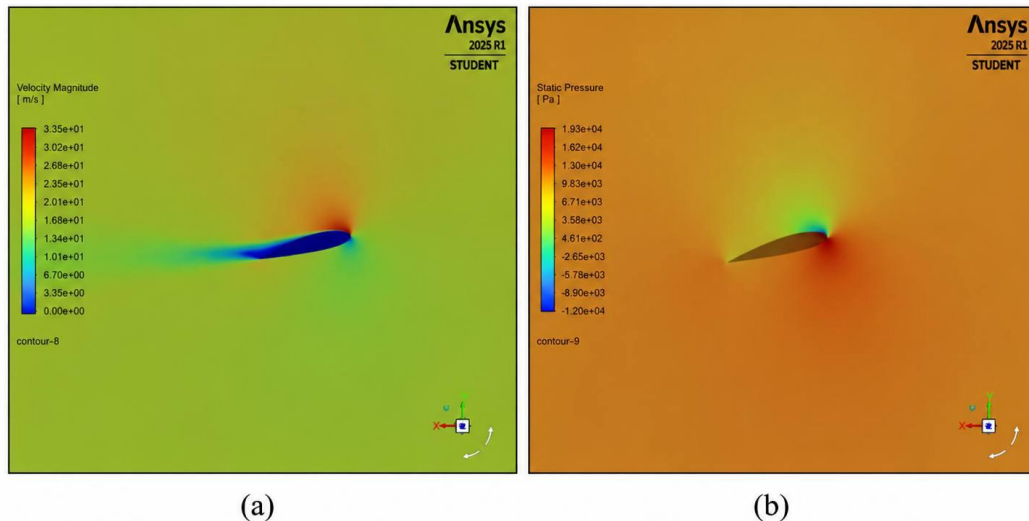


Figure 9. Velocity and static-pressure distributions around the baseline semi-wing at $V=30$ m/s and $\alpha=12^\circ$: (a) velocity magnitude and (b) static pressure.

5.2 Aerodynamic Performance at 30 m/s

5.2.1 Lift Coefficient

As shown in Figure 10, C_L generally increases up to $\alpha=10^\circ$ – 12° . The blended winglet produces the largest improvements at 0° , 4° , and 12° , equal to 32.4%, 23.5%, and 12.9%, respectively. The split-tip winglet performs best at 7° , 10° , and 15° , with improvements of 22.84%, 22.70%, and 9.96%, respectively. The plate-type configurations produce smaller lift gains than the blended and split-tip winglets.

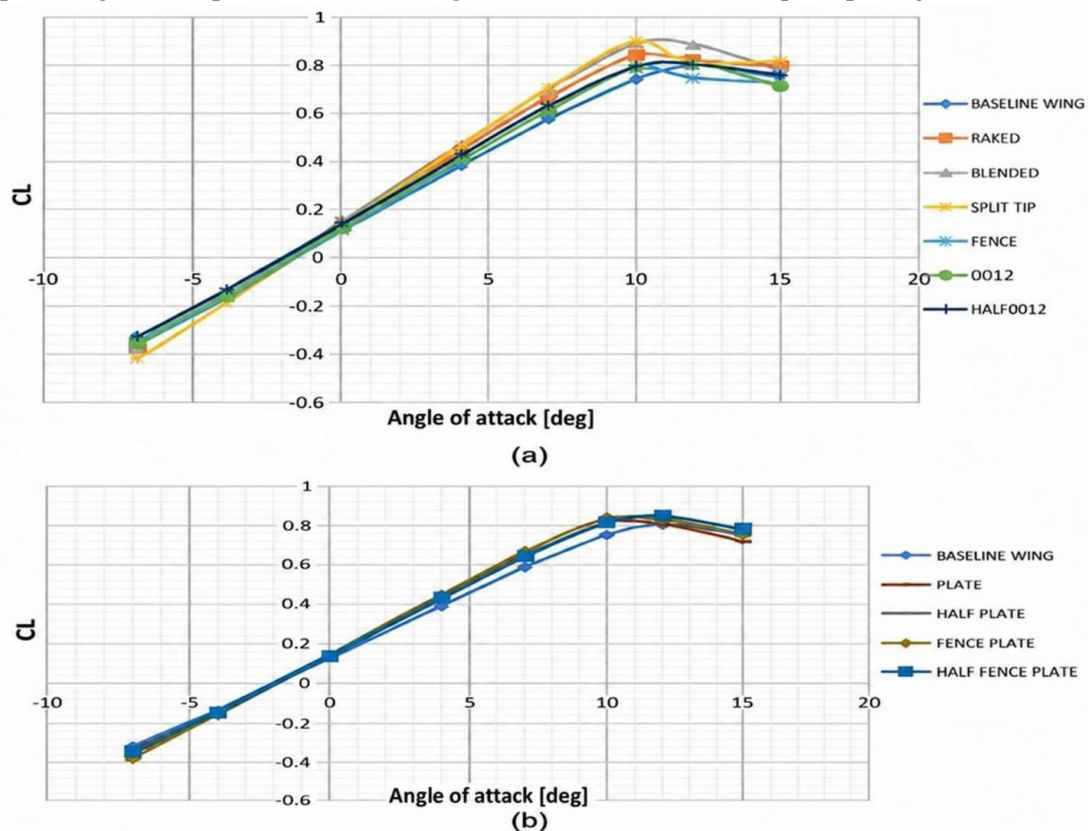


Figure 10. Lift coefficient versus angle of attack at $V=30$ m/s: (a) airfoil-based and (b) plate-type winglets, each compared with the baseline wing.

5.2.2 Drag Coefficient

As shown in Figure 11, all winglets increase C_D relative to the baseline wing over $\alpha \geq 0^\circ$. The lowest penalties are produced by the raked winglet at 0° , 4° , and 7° , with 13.7%, 9.8%, and 7.3%, respectively; the half NACA 0012 winglet at 10° and 15° , with 6.88% and 2.57%; and the full NACA 0012 winglet at 12° , with 10.33%. The largest increases are caused by the plate winglet at 0° , 4° , 7° , and 10° , with 100.7%, 66.8%, 44.2%, and 30.5%; the split-tip winglet at 12° , with 38.6%; and the fence-plate winglet at 15° , with 15.47%.

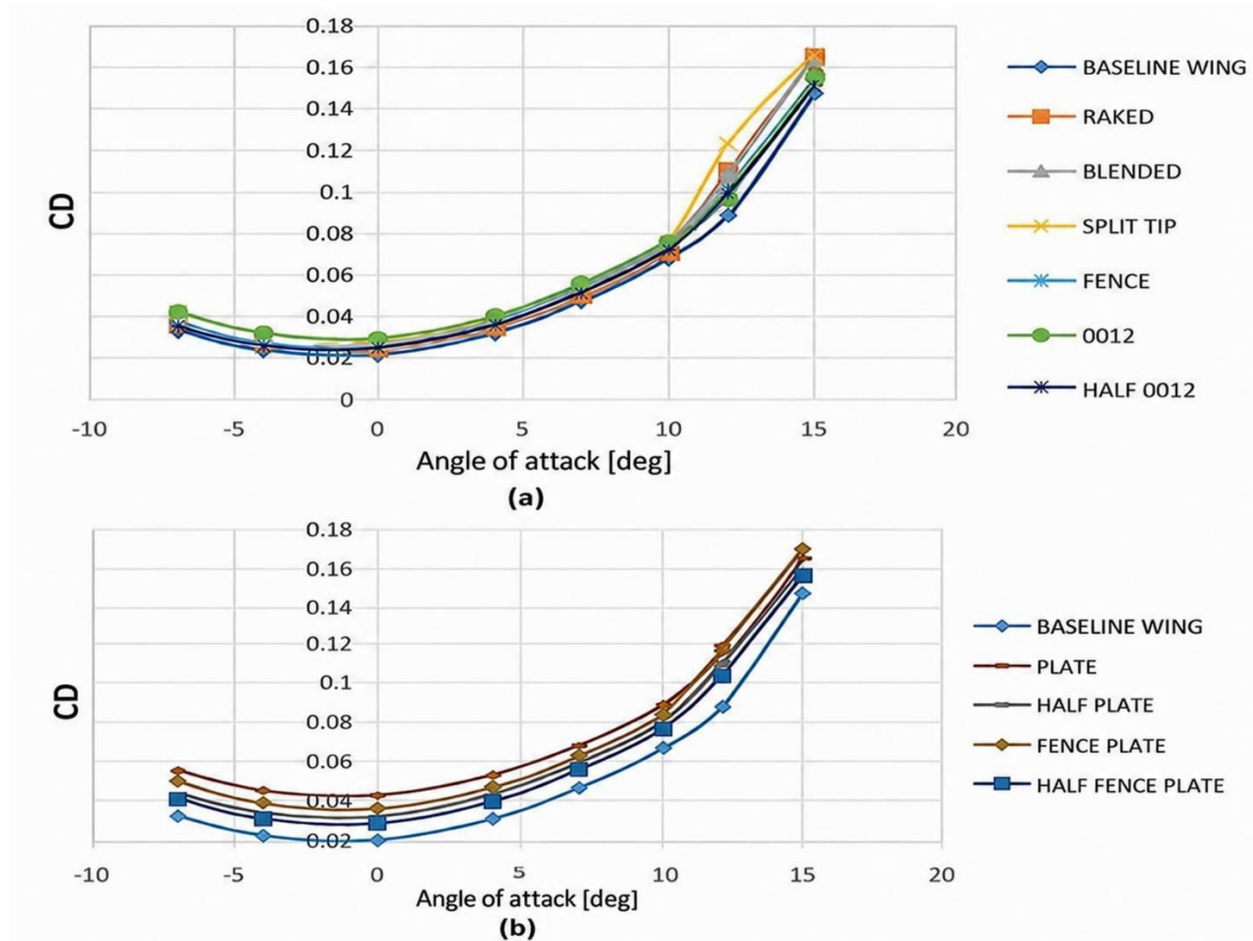


Figure 11. Drag coefficient versus angle of attack at $V=30$ m/s: (a) airfoil-based and (b) plate-type winglets, each compared with the baseline wing.

5.2.3 Aerodynamic Efficiency C_L/C_D

As shown in Figure 12, the blended winglet achieves the highest efficiency from 0° to 10° , with improvements of 12.38%, 6.76%, 7.80%, and 7.64%, respectively. The raked winglet ranks second at 0° , 4° , and 7° , with 7.94%, 6.02%, and 7.47%, while the split-tip ranks second at 10° with 7.29%, followed by the raked winglet with 6.45%. At 12° , the blended and full NACA 0012 winglets show the smallest losses of 7.38% and 7.83%, whereas the split-tip shows the largest loss of 26.61%. At 15° , the half NACA 0012, split-tip, and half-fence-plate winglets show the smallest losses of 1.55%, 2.38%, and 2.54%, while the plate winglet produces the largest loss of 15.89%. The relatively small efficiency loss of the split-tip winglet at 15° is mainly attributed to the substantial reduction in the baseline-wing C_L/C_D at this high angle of attack. Consequently, the relative difference between the split-tip and baseline configurations becomes smaller at 15° than at 12° .

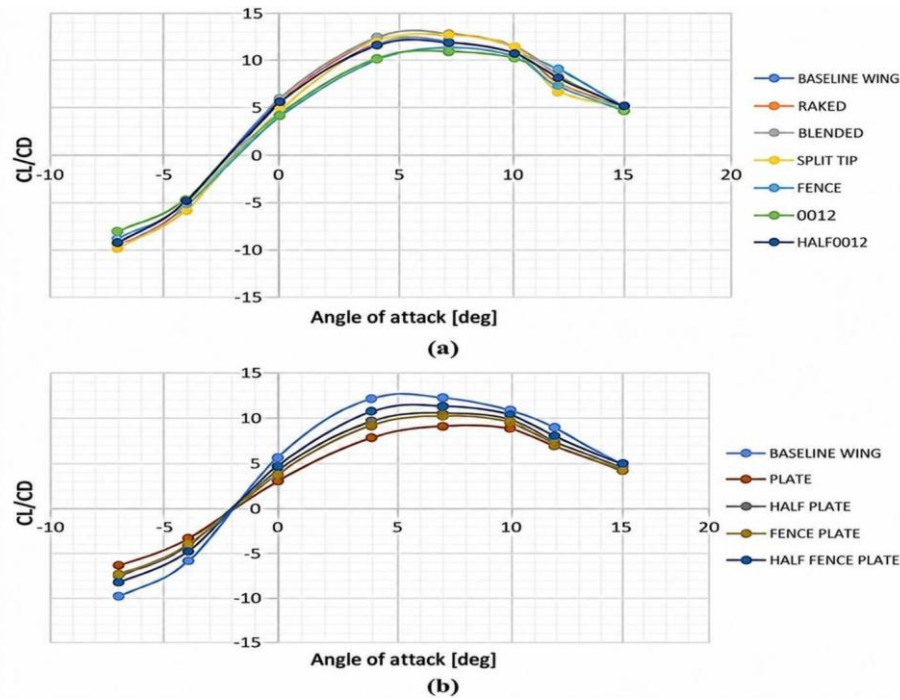


Figure 12. Lift-to-drag ratio versus angle of attack at $V=30$ m/s: (a) airfoil-based and (b) plate-type winglets, each compared with the baseline wing.

5.3 Aerodynamic Performance at 10 m/s

5.3.1 Lift Coefficient

As shown in Figure 13, the blended winglet gives the highest C_L gains of 25.74% and 22.45% at 0° and 4° , respectively. The split-tip leads at 7° and 10° with 20.56% and 17.28%, narrowly exceeding the blended winglet with 20.04% and 17.13%. At 12° , the half-fence-plate achieves 14.79%; at 15° , the fence-plate and half-fence-plate achieve 5.75% and 5.20%, respectively.

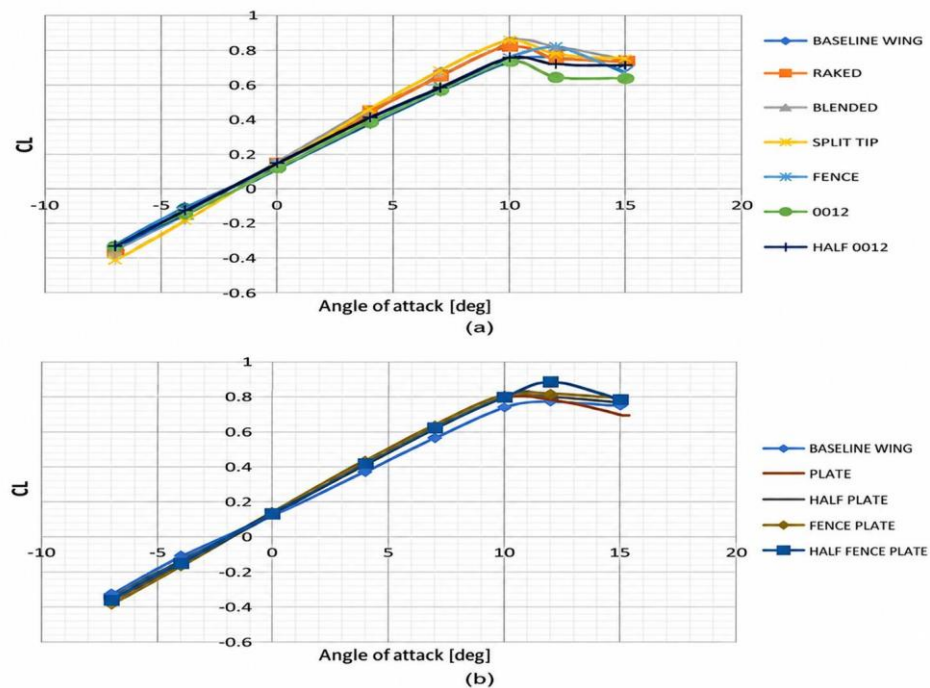


Figure 13. Lift coefficient versus angle of attack at $V=10$ m/s: (a) airfoil-based and (b) plate-type winglets, each compared with the baseline wing.

5.3.2 Drag Coefficient

As shown in Figure 14, all winglets increase C_D relative to the baseline wing over $\alpha \geq 0^\circ$. The smallest penalties are 12.95% for the raked winglet at 0° ; 9.45%, 7.22%, and 3.92% for the half-plate at 4° , 7° , and 10° ; 2.16% for the fence at 12° , followed by 5.85% for the half-fence-plate; and 3.59% for the half-plate at 15° . The plate winglet causes the largest increases from 0° to 10° , reaching 88.10%, 62.73%, 43.59%, and 29.06%, while the split-tip produces the highest penalties at 12° and 15° , equal to 33.56% and 24.16%, respectively.

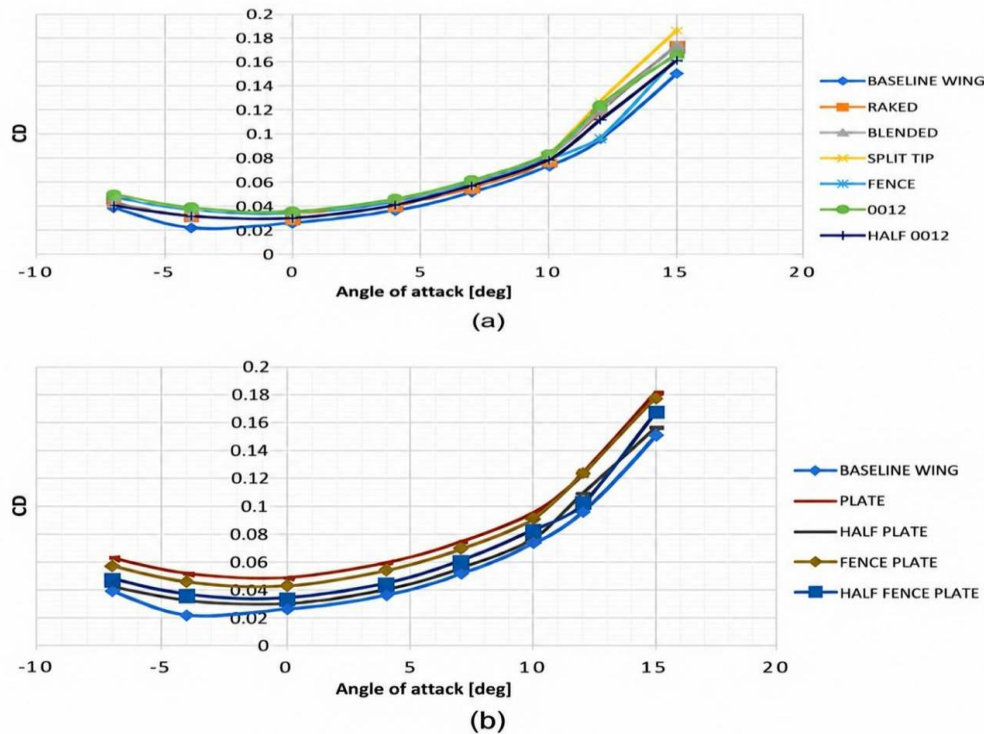


Figure 14. Drag coefficient versus angle of attack at $V=10$ m/s: (a) airfoil-based and (b) plate-type winglets, each compared with the baseline wing.

5.3.3 Aerodynamic Efficiency C_L/C_D

As shown in Figure 15, the blended winglet achieves the highest efficiency from 0° to 10° , with improvements of 7.41%, 7.06%, 6.94%, and 6.72%, respectively. The raked winglet ranks second with 6.34%, 6.75%, 6.29%, and 5.41%. Among the plate-type configurations, only the half-plate exceeds the baseline at 4° , 7° , and 10° , by 0.98%, 2.19%, and 3.53%. At 12° , the half-fence-plate and fence winglets improve efficiency by 8.45% and 4.62%. At 15° , all configurations are less efficient; the half-plate shows the smallest loss of 1.34%, whereas the full NACA 0012 produces the largest reduction of 23.08%.

5.4 Reynolds-Number Effect and Overall Assessment

Increasing the velocity from 10 to 30 m/s improves the baseline-wing C_L/C_D by 14.35%, 15.29%, 10.80%, 8.19%, and 12.16% at 0° , 4° , 7° , 10° , and 12° , respectively, but by only 3.01% at 15° . The blended winglet remains the most efficient from 0° to 10° , while the raked winglet provides relatively low drag penalties. The split-tip generates high lift at 7° and 10° , but with increasing drag. At 12° , the half-fence-plate improves efficiency by 8.45% at 10 m/s, whereas the blended winglet shows the smallest loss of 7.38% at 30 m/s. At 15° , the smallest losses are 1.34% for the half-plate at 10 m/s and 1.55% for the half NACA 0012 at 30 m/s. The plate winglet generally produces the greatest drag and efficiency penalties.

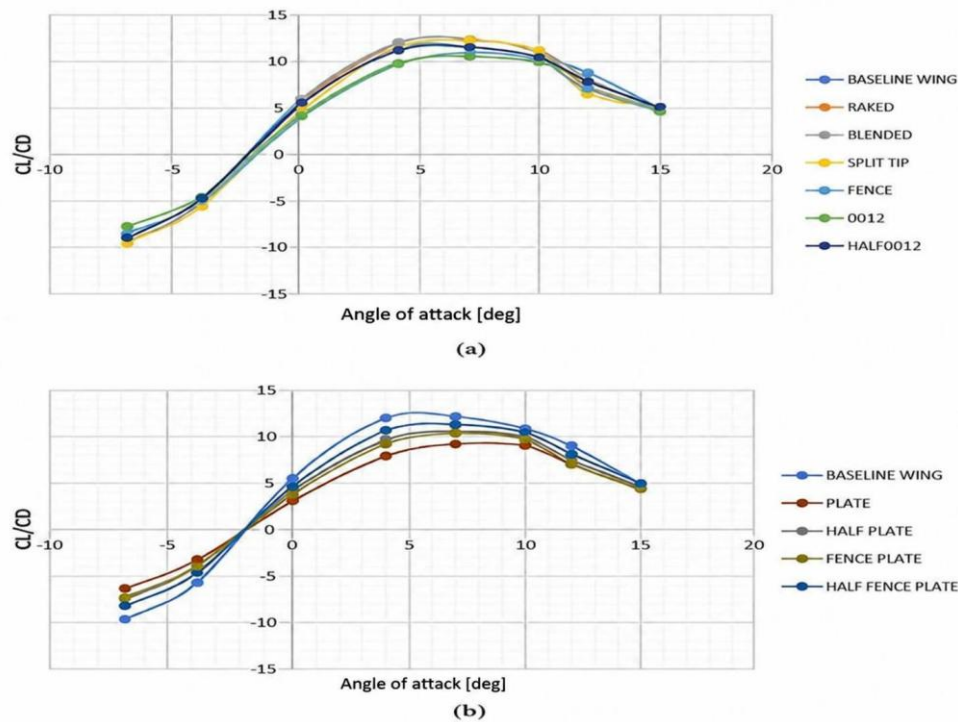


Figure 15. Lift-to-drag ratio versus angle of attack at $V=10$ m/s: (a) airfoil-based and (b) plate-type winglets, each compared with the baseline wing.

6. Conclusions

Ten winglet configurations are numerically evaluated on a rectangular NACA 2415 semi-span wing at 10 and 30 m/s. The baseline-wing lift and drag results show generally good agreement with published numerical data, particularly at low and moderate angles of attack. Winglet performance depends on geometry, angle of attack, and Reynolds number; therefore, no configuration is optimal over the entire operating range.

The blended winglet achieves the highest C_L/C_D over $0^\circ \leq \alpha \leq 10^\circ$, with improvements of 6.72%–12.38%. The split-tip winglet produces the highest lift gains at 7° and 10° , reaching 22.84% and 22.70% at 30 m/s and 20.56% and 17.28% at 10 m/s, although with increasing drag. The raked winglet provides a favorable balance between lift improvement and aerodynamic efficiency. All winglets increase C_D at positive angles of attack, while the plate winglet generally causes the greatest penalties. At 12° , the half-fence-plate improves C_L/C_D by 8.45% at 10 m/s, whereas no winglet exceeds the baseline efficiency at 30 m/s. At 15° , the smallest efficiency losses are 1.34% for the half-plate at 10 m/s and 1.55% for the half NACA 0012 at 30 m/s. Increasing the velocity improves the baseline efficiency by 8.19%–15.29% over $0^\circ \leq \alpha \leq 12^\circ$. Overall, winglet selection should be based on the intended angle of attack and Reynolds number rather than a single performance criterion.

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