

HIGH LIFT CONTROL WITH A CFJ AROUND A NACA 4415 AIRFOIL

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ABSTRACT: An active concept of lift control around a NACA 4415 airfoil has been presented in this paper. On the upper surface, geometric modifications were implemented where the blowing and suction were localized relative to the leading edge. In order to validate the mathematical model, a baseline NACA 4415 airfoil was examined and compared with experimental data. Several numerical investigations were considered in which the blowing's localization and momentum coefficient were modified. These configurations were tested at a velocity of 21 meters per second with angles of attack ranging from 0 to 40 degrees. The CFD results show that the CFJ concept is quite promising, and that by pushing the stall to atypical angles of attack, it can offer a significant increase in lift force and a delay in boundary layer separation. However, several analytical correlations for predicting the coefficient of maximum lift as a function of the blowing position and the coefficient of momentum have been established.

KEY WORDS: CFJ, NACA 4415, Blowing, Suction, CFD, Jet Momentum, Lift, Correlation.

NOMENCLATURE

A : Area	C_μ : Momentum coefficient
AoA : Angle of attack	C_p : Pressure coefficient
C : Chord	F : Resultant force
CFD : Computational fluid dynamics	FC : Flow control
CFJ : Co-flow jet	$\dot{m}$: Mass flow rate
SA : Spalart Allmaras	L : Lift
CL : Lift coefficient	p : Static pressure
R : Force from airfoil surface integral	R' : Reaction force of R
Re : Reynolds number	S : Wing span area ($b \times chord$)

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θ : Angle between slot surface and the line normal to chord	y^+ : Non-dimensional length scale for turbulent boundary layer
j : Jet injection	t : Thickness of profile
∞ : Freestream	V : Velocity vector
U, V : Velocity components in x and y direction	g : Body accelerations acting on the continuum
ρ : Density	μ : Fluid viscosity
d : Distance from the field point and the nearest wall	Cb1.etc : Empirical constants in the turbulence model
ν : Kinematic viscosity	X : Chordwise direction
x, y : Streamwise coordinate	i, j, k : Cartesian coordinates
$CL_{\max}$: Maximal lift coefficient	X_C : Injection slot's location
Y_S : Injection and suction slot's size	: (x_C/C)

1 INTRODUCTION

One of the most vital aerodynamic organs of a flying machine is the wing, which allows it to fly in the air efficiently. The flow around the wing is very sensitive to changes in the angle of attack. Beyond a value, there is a phenomenon of the boundary layer separation on the upper surface which causes instability and a total degradation of aerodynamic performance called stall. Scientists and engineers have been faced with a great challenge to minimize the adverse effects of the stall and further control the flows since the publication of the first reviews of boundary layer theory developed by Prandtl [1]. Controlling flow around an airfoil, on the other hand, has become a research topic in the aeronautics discipline. Passive and active controls are two methods for controlling flow around a wing to increase its aerodynamic performance. In the experiment, several methods such as vortex generators, vortex manipulators, suction, and blowing were frequently used to solve this problem with variable degrees of success. A vast literature accumulated over the years has indeed been reviewed by several authors such as Goldstein [2], Lachmann [3], Rosenhead [4], Schlichting [5], and Chang [6]. The means of control have been classified into two categories by Gad-el-Hak [7], in contrast to so-called active controls, passive controls do not require any external energy input. Thus, active control is said to be predetermined if it does not require sensors to know the state of the system. On the other hand, active control is said to be reactive if it requires sensors. Depending on the position of the sensors in the loop, it can be open or closed. However, we can add the distinction among the active control means between stationary and unsteady actuators. Flow control actuators such as suction and blowing have long been employed around obstacles. In 1904, permanent blowing was applied around a cylinder to delay the separation of the boundary layer [1]. Both oscillatory blowing and permanent tangential blowing have been applied to achieve improved lift on an

airfoil NACA 0015 by Seifert et al. (1993) [8]. This study revealed that less energy was required for an oscillatory blast to achieve the same lift as permanent blowing.

As a relatively new active flow control technology, the co-flow jet (CFJ) has been suggested by Zha and Paxton [9]. So, an output slot near the leading edge and an inlet slot near the trailing edge generate the blowing and suction over an airfoil, where air is then recirculated. This process which consists in tangentially injecting fluid at high velocity into the boundary layer is very efficient and simpler to implement. The main-flow is attached when injection and suction are used in the CFJ airfoil with resistance against the unfavorable pressure gradient, especially at high angles of attack. They are one of the active approaches for controlling the separation of the boundary layer around an airfoil. Their goal is to provide energy to the air particles in the boundary layer separation zones, as well as to generate vortex structures that will homogenize and control the velocity near the wall. In the aviation industry, the compressed air required for blowing is supplied using air taken from the compressor stages of an aircraft engine. Another alternative approach is to generate compressed air by compact electric compressors which are integrated into the wing. The effects of CFJ on a NACA 0025 airfoil at a Reynolds number of 3.8×10^5 have been investigated by Zha et al. [10]. They examined a range of different momentum coefficients by using a thin wire at the front of the airfoil to produce flow turbulence. According to their findings, the airfoil with CFJ had a maximum lift of 2.2 times that of the baseline airfoil. Lefebvre et al. [11] presented a computational design of an electric aircraft applying active control around a wing with blowing and suction. The goal of this numerical study is to design an aircraft with high wing loading and compact size in order to carry more battery and achieve greater range. They concluded that the aircraft can cruise with a very high lift coefficient of the order of 1.3, which produces a wing loading three times that of a conventional general aviation aircraft. The aerodynamic performance of an airfoil has been developed on the upper surface of a NACA 0012 airfoil using active flow control with blowing and suction in [12]. The CFD code based on the Navier-Stokes equations (RANS) are performed by changing the blowing angle. However, as conclusion of this study, the co-flow jet technology with variable injection angle can be used more in order to increase the aerodynamic performance of an aerodynamic airfoil. Yang et al. [13] studied how to improve a maximum lift coefficient using active flow control blowing and suction around an airfoil. The authors have demonstrated that the $CL_{\max}$ can greatly exceed the following formula established by Smith's pioneering research [14]:

$$(1) \quad CL_{\max} = 2\Pi(1 + t/C) .$$

Xu et al. [15] investigate the effects of injection slot size, injection slot location, suction slot size, and suction slot location. To obtain the best possible design and

to better anticipate flow separation, they use a CFD code with a two-equation $k - \omega$ (SST) turbulence model. As a result of their efficiency and efficacy in suppressing the separation of the airfoil at high incidence, they have adjusted perfect locations for blowing and suction and optimizing their sizes.

In the present study, the 2D subsonic turbulent flows around several modified NACA 4415 airfoils were analyzed. A co-flow jet: blowing and suction are installed on the upper face of these airfoils (see Fig. 1). Three blowing positions were considered: $X/C = 5, 10$ and 15% from the leading edge. On the other hand, a fixed position of the suction was taken at 85% of the chord in all of the cases studied. The size of the blowing and suction slot is adopted constant $y_s/C = 1.0\%$ for all cases studied. In addition, the effect of changing the jet momentum coefficient parameter C_μ on the lift was investigated using the following values: $C_\mu = 0.1, 0.2, 0.3$ and 0.4 . However, a series of numerical simulations were carried out in order to estimate the coefficient of lift for a velocity of 21 meters per second over a range of angles of attack from 0° to 40° . The Spalart-Allmaras turbulence model [16] is used to complete the Navier-Stokes transport equations in order to correctly predict the complex flow around the airfoil.

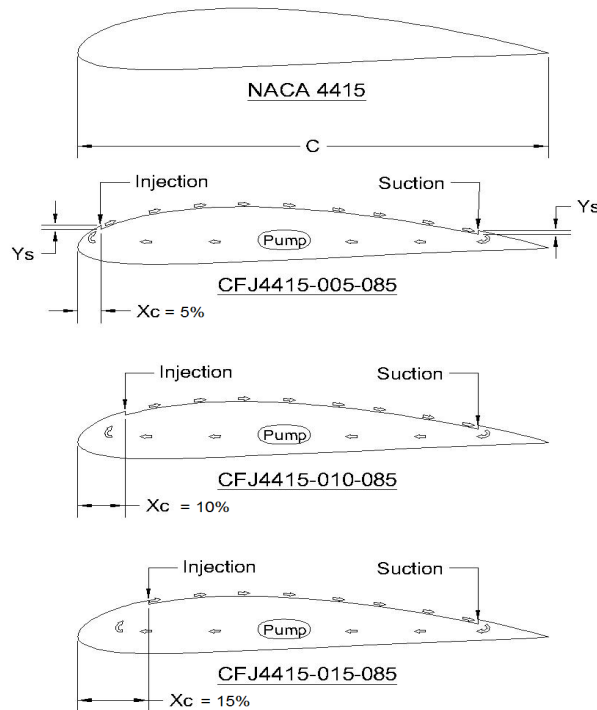


Fig. 1: Co-flow jet configuration around a modified NACA 4415 airfoil.

2 TRANSPORT EQUATIONS AND TURBULENCE MODEL

The flow around the airfoil is considered as turbulent and subsonic. In Cartesian coordinates, the general forms of the transport equations are as follows:

2.1 CONTINUITY EQUATION

$$(2) \quad \frac{\partial}{\partial x_j} (\bar{\rho} \tilde{U}_j) = 0.$$

2.2 MOMENTUM CONSERVATION EQUATION

$$(3) \quad \frac{\partial}{\partial x_j} (\bar{\rho} \tilde{U}_i \tilde{U}_j) = \bar{\rho} g_i - \frac{\partial \bar{p}}{\partial x_i} - \frac{\partial}{\partial x_j} (\rho u_i'' u_j'') + \frac{\partial}{\partial x_j} \left[\bar{\mu} \left(\frac{\partial \tilde{U}_i}{\partial x_j} + \frac{\partial \tilde{U}_j}{\partial x_i} \right) - \frac{2}{3} \bar{\mu} \frac{\partial \tilde{U}_k}{\partial x_k} \delta_{ij} \right].$$

2.3 TURBULENCE MODEL

The turbulence model employed in this study is one proposed by Spalart and Allmaras [16], which includes a transport equation for the ν quantity

$$(4) \quad \frac{\partial(\bar{\rho}\tilde{\nu})}{\partial t} + \vec{\nabla} \cdot (\bar{\rho} \vec{V} \tilde{\nu}) = \vec{\nabla} \cdot \left[\frac{\bar{\mu} + \bar{\rho}\tilde{\nu}}{\sigma_{SA}} \vec{\nabla} \tilde{\nu} \right] + P_v - D_v.$$

Alternatively, the following expressions define the terms of production and destruction:

$$(5) \quad P_v = C_{b1} C_\mu \tilde{S} \bar{\rho} \tilde{\nu} + C_{b2} \frac{\bar{\rho} (\vec{\nabla} \tilde{\nu})^2}{\sigma_{SA}},$$

$$(6) \quad D_v = C'_{\omega 1} f_\omega \frac{\bar{\rho} (\vec{\nabla} \tilde{\nu})^2}{\rho d^2}$$

with

$$(7) \quad f_x = g \left(\frac{1 + C_{\omega 3}^6}{g^6 + C_{\omega 3}^6} \right)^{1/6} \quad \text{and} \quad g = r + C_{\omega 2} (r^2 - r)$$

and

$$(8) \quad M_t = \bar{\rho} \tilde{\nu} \frac{\chi^3}{\chi^3 + C_{v1}} \quad \chi = \frac{\bar{\rho} \tilde{\nu}}{\mu}.$$

The closure coefficients are given by the following values:

$$(9) \quad \begin{aligned} \sigma_{SA} &= \frac{2}{3}; & C_{b1} &= 0.1355; & C_{b2} &= 0.622; \\ C_{v1} &= 7.1; & C_{\omega 1} &= 0.3; & C_{\omega 2} &= 2. \end{aligned}$$

(For more information see [16].)

3 BLOWING AND SUCTION PARAMETERS

3.1 LIFT COEFFICIENT CALCULATION

The directions of blowing and suction are oriented in regard to the chord direction by two angles θ_1 and θ_2 , which are taken to be zero in our study. The momentum and pressure at the blowing and suction slots produce a reaction force, which should be incorporated in the CFD code software used to appropriately estimate the lift force. However, Zha et al. [14] produced the revised lift formulation using the flow parameters at the blowing and suction slots:

$$(10) \quad F_{ycfj} = (\dot{m}_{j1} V_{j1} + p_{j1} A_{j1}) \sin(\theta_1 - AoA) + (\dot{m}_{j2} V_{j2} + p_{j2} A_{j2}) \sin(\theta_2 + AoA).$$

The airfoil's total lift can then be represented as

$$(11) \quad L = R'_y - F_{ycfj}.$$

3.2 JET MOMENTUM COEFFICIENT

The co-flow jet momentum coefficient C_μ , which is used to evaluate the blowing and suction intensity, is defined as

$$(12) \quad C_\mu = \frac{\dot{m} V_j}{\frac{1}{2} \rho_\infty V_\infty^2 S}.$$

3.3 GEOMETRY

To help the user to identify these modified airfoils, a reference is assigned to each modified airfoil, such as CFJ4415-00X-00Y, where the X and Y represent the blowing and suction locations, respectively.

4 BOUNDARY CONDITIONS AND MESHING SETUP

The 2D structured meshes are generated using the rectangular-calculation domain topology with dimensions of $30C \times 3C$ as shown in Fig. 2, the chord length of the

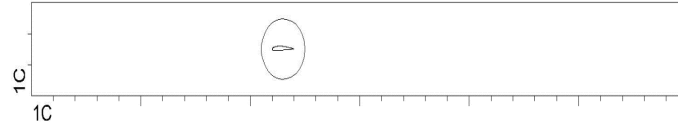


Fig. 2: Calculation domain around NACA 4415.

airfoil is $C = 0.15$ m. This computational domain is composed with a single input, a single output, and two lower/upper walls. The airfoil is $11C$ away from the inlet boundary and $18C$ away from the outlet boundary. The computational domain is formed by two blocks: a circular one with an aerodynamic airfoil inside it, and a block outside it that corresponds to the outer domain's boundaries. Before coupling the two interfaces, the angle of attack is set by rotating the circular block. Figures 3 and 4 also indicate that the considered mesh is a two-dimensional structured mesh that is variable depending on the blowing locations and the angle of attack. Furthermore, the meshing must attain an appropriate skewness in order for the solution to converge.

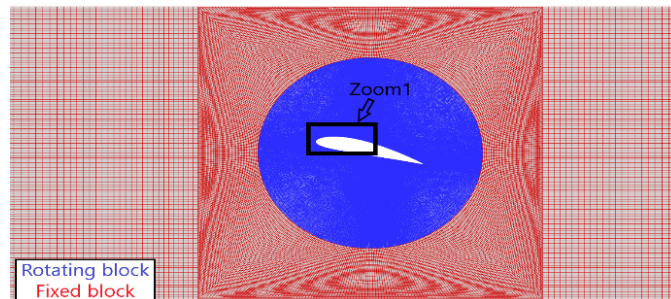


Fig. 3: Meshing of computational domain.

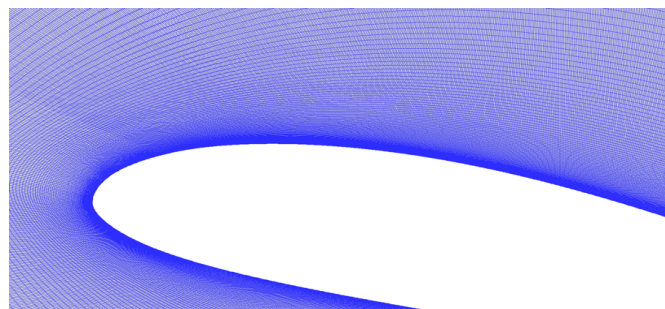


Fig. 4: (Zoom1) Meshing around the profile.

5 RESULTS AND DISCUSSION

In this numerical investigation, a CFD code was used to analyze the turbulent flows around a modified NACA 4415 airfoils using the RANS model coupled with turbulence model: Spalart-Allmaras. In relative to the leading edge, three blowing positions were considered: $X_b/C = 5, 10$, and 15% . At 85% of the leading edge, the suction location was set. In addition, different values of the jet momentum coefficient parameter $C\mu$ have been adjusted in order to investigate the impact of the blowing and suction parameters on the modified airfoil's aerodynamic performance. However, a series of numerical simulations were conducted to determine the coefficient of lift for a velocity of 21 meters per second at angles of attack ranging from 0 to 40 degrees.

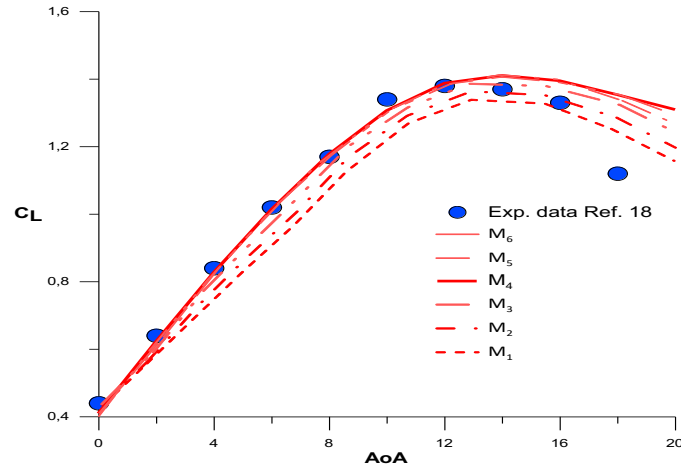
5.1 GRID INDEPENDENCE AND NACA 4415 AIRFOIL VALIDATION

To select the optimal number of nodes to use in the meshing procedure, six computational grids were inspected as it shown in Table 1 in the case of a flow around the baseline NACA 4415 airfoil. And this is done to ensure that the simulation's results are unaffected by grid size. This is accomplished by running cases with an increasing number of grid nodes until the CFD results become autonomous of grid size and coincide with a result from the literature.

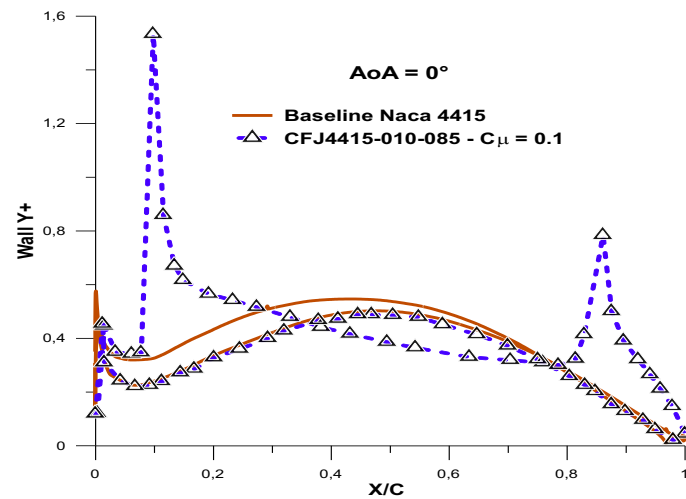
Table 1: Several grids used

Grids	M1	M2	M3	M4	M5	M6
No of nodes	300×90	300×100	320×120	370×120	420×120	420×180

Figure 5 shows the computational variation of the lift coefficient as a function of angle of attack for six different grids compared with the wind tunnel data presented by Fouatih [18]. The present study employing M4, M5, and M6 mesh and the experimental data of in [18] demonstrate good agreement in the quasi-linear zone with respect to M1, M2, and M3. The differences between the current study and the measured curve, can be seen by examining at the stall zone. It is clear that CFD is far from predicting the stall phenomenon because the turbulence models used are not precise for flows with separate streams. Based on this analysis, it was determined that CFD's limiting use is post-stall, that is, at angles of attack larger than 12° and $CL_{\max} = 1.4$. The numerical results for the last three grids (M4, M5, and M6) remain almost the same as the number of nodes increases. However, further refining the mesh does not improve substantially the calculated precision; it considerably increases the computation times. Consequently, the grid M4 is considered as favorable for all the numerical simulations of all the cases of airfoils considered.

Fig. 5: Lift coefficient vs AoA for the baseline NACA 4415 airfoil.

The final step in the grid convergence inspection was to check into the evolution of wall $Y+$ along the airfoil chord. Figure 6 shows the longitudinal evolution of the $Y+$ wall around two airfoils using the grid M4: baseline NACA 4415 and CFJ4415-010-085 - $C_{\mu} = 0.1$ with an angle of attack $AoA = 0^\circ$. The existence of two peaks at the blowing and suction locations distinguishes the modified airfoil from the baseline NACA 4415 airfoil. The two investigated airfoils have significantly low

Fig. 6: Evolution of wall $Y+$ along the airfoil for M4 grid.

wall $Y+$ values, indicating that the grid size is fine and dense near the wall, allowing for the capture of all effects near the wall, i.e. in the viscous underlayer. This result supports the use of the M4 grid.

5.2 RESULTS OF SIMULATIONS FOR VARIOUS BLOWING CONDITIONS

The results of the current simulations in the case of the co-flow jet establishment for NACA4415-005-085, NACA4415-010-085, and NACA4415-015-085 airfoils are shown in Figs. 7, 8, and 9: variations in the lift coefficient as a function of angle of attack AoA are shown, grouped by values of momentum coefficients C_μ ranging from 0.1 to 0.4, and compared to the baseline NACA 4415 lift coefficient. When compared to the baseline NACA 4415 airfoil, airfoils with co-flow jet have greater lift coefficients for all angles of attack, and this gain in CL is followed by an increase in C_μ . However, we note that the coefficients of lift of modified airfoils are significantly larger than the baseline for zero angle of attack. Also, the stall angles corresponding to CL_{max} have been seen to be pushed back to unusual angles of attack, creating a delay in the separation of the boundary layer and increasing the lift enhancement around the stall angles. The values of maximum lift coefficients and corresponding angles obtained for all of the airfoil cases studied are summarized in Table 2. In comparison to the airfoils CFJ4415-010-085 and CFJ4415-015-085, we find that the aerodynamic airfoil CFJ 4415-005-085 with $C_\mu = 0.4$ provides the best aerodynamic performance in terms of maximum lift. Also, in comparison with other research, such as references [19] and [20], the presence of CFJ causes an increase

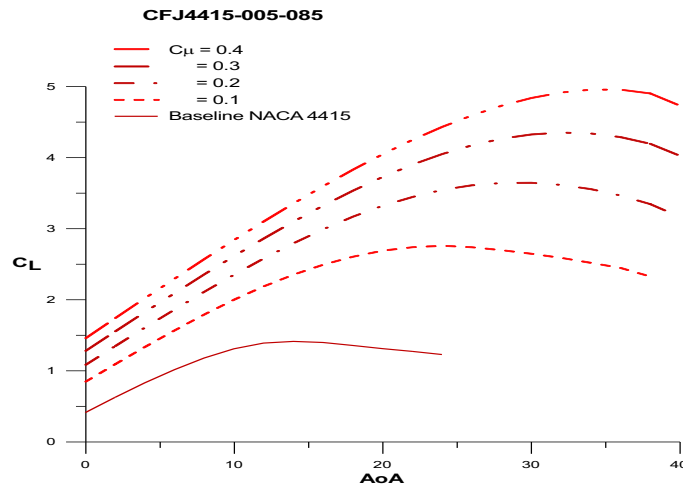


Fig. 7: Lift coefficient vs AoA for the modified NACA 4415 – injection slot at 5%.

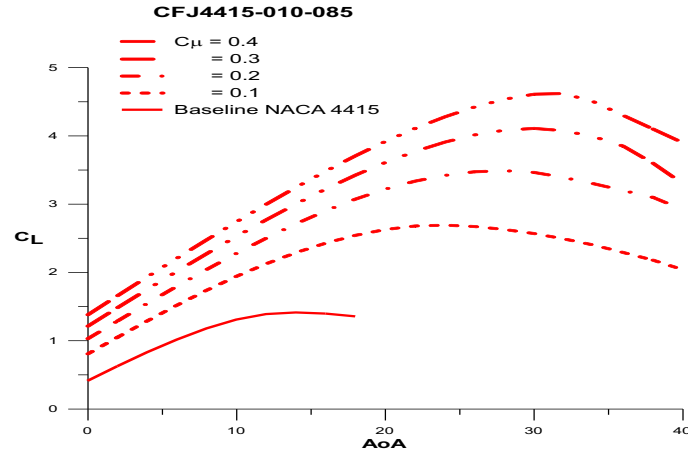


Fig. 8: Lift coefficient vs AoA for the modified NACA 4415 – injection slot at 10%.

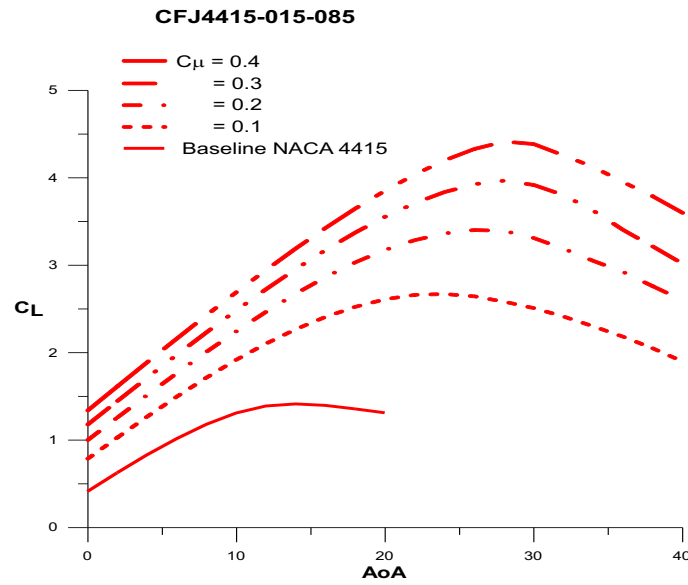


Fig. 9: Lift coefficient vs AoA for the modified NACA 4415 – injection slot at 15%.

in CL_{max} and causes the stall angle of attack to be pushed to unusual angles (see Table 2). Finally, the blowing flow extends beyond the leading edge of the airfoil, causing a delay in boundary layer separation. This delay is caused by the presence of a turbulent mixture layer between the blowing and the main flow, which energizes the wall's boundary layer and so enhances circulation, resulting in a lift gain.

Table 2: $CL_{\max}$ values for all of the cases studied and from a variety of research papers

Airfoils	$C\mu$	$CL_{\max}$	$\Delta CL_{\max}$ (%)	$AoA^\circ (CL_{\max})$
NACA 4415	—	1.41	—	14
CFJ4415-005-085	0.1	2.76	95	24
	0.2	3.64	158	30
	0.3	1.35	208	32
	0.4	4.95	350	34
CFJ4415-010-085	0.1	2.69	90	24
	0.2	3.49	147	28
	0.3	4.11	191	30
	0.4	4.62	227	32
CFJ4415-015-085	0.1	2.76	95	24
	0.2	3.40	141	26
	0.3	3.96	180	28
	0.4	4.41	212	30
CFJ S809 ref. [19]	0.01	1.61	45	15
CFJ NACA 2415 ref. [20]	0.05	2.69	88.52	19

Figure 10 shows the evolution of the lift coefficient CL as a function of the momentum coefficient $C\mu$ for the three modified airfoils in the situation of zero incidence ($AoA = 0^\circ$). For the three cases considered, it is shown that the coefficient of lift grows in a quasilinear fashion and with about the same slope as the coefficient $C\mu$. Therefore, an efficiency increase in lift for zero incidence is concluded of the order of $\Delta CL / \Delta C\mu \cong 2$.

For the various airfoils investigated, Fig. 11 describes the relation between the maximum lift coefficient $CL_{\max}$ and the moment coefficient $C\mu$. For each investigation, these evolutions were shown to be quasi-linear and can be linked to the correlations listed in Table 3. These correlations show that when $C\mu = 0$, $CL_{\max}$

Table 3: Correlation of $CL_{\max} = f(C\mu)$

Airfoils	Correlation
CFJ4415-005-085	$CL_{\max} = 7.3C\mu + 2.10$
CFJ4415-010-085	$CL_{\max} = 6.4C\mu + 2.12$
CFJ4415-015-085	$CL_{\max} = 5.8C\mu + 2.16$

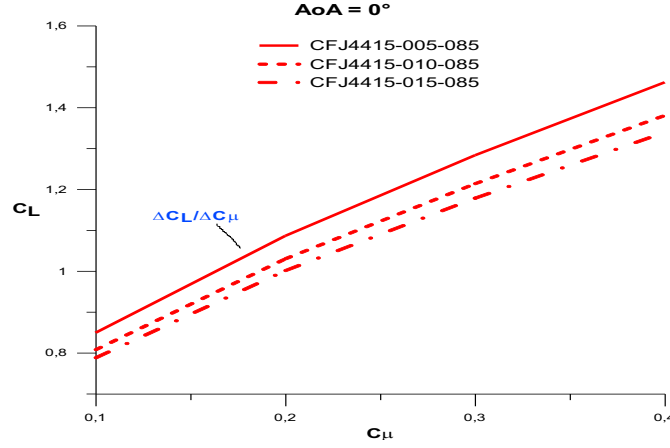


Fig. 10: Variation of the lift coefficient with the momentum coefficient at the zero angle of attack.

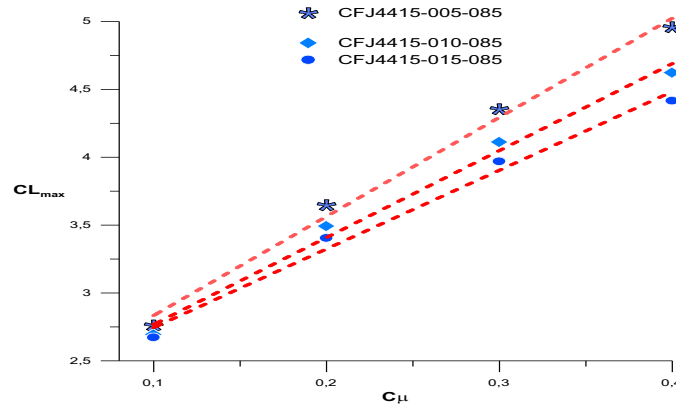


Fig. 11: Variation of the maximum lift coefficient with the momentum coefficient.

is 2.1, which is considerably different from the $CL_{\max}$ of a baseline NACA 4415 airfoil, indicating that these equations do not apply to airfoils without CFJ.

In order to define an expression regrouping at the same time the maximum value of the lift coefficient $CL_{\max}$, the momentum coefficient $C\mu$ and the position of the blowing X_b/C , a correlation has been developed as it shown in expression (13). This last is validated for any $C\mu \in [0.1 - 0.4]$ and $X_b/C \in [0.05 - 0.15]$ with an error of 5%.

$$(13) \quad CL_{\max} = C\mu[8 - 15(X_b/C)] + 2.1.$$

Therefore, it is noted that all the values of CL_{max} mentioned in Table 1 are verified with this correlation. Other parameters such as airfoil thickness, Reynolds number, and suction location should be added in this correlation to make it more universal. As a conclusion, this correlation can only be applied to the modified airfoils used in this study.

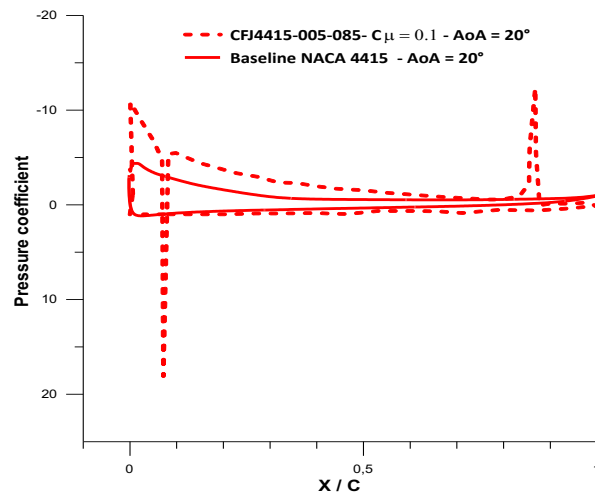


Fig. 12: Influence of blowing and suction on distribution of the pressure coefficient.

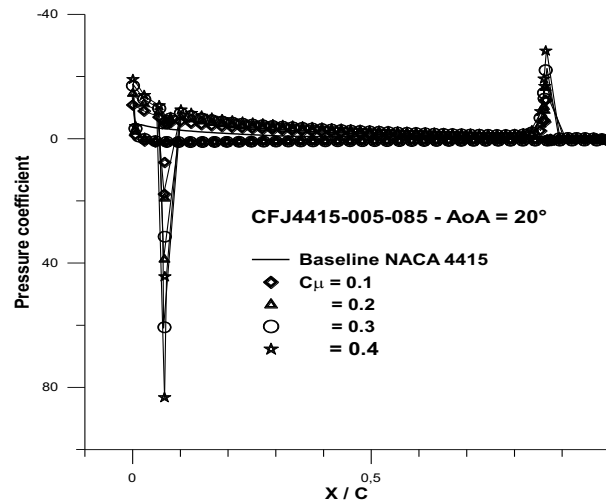


Fig. 13: Distribution of the pressure coefficient with respect to X/C for the airfoil CFJ4415-005-085.

In Fig. 12 a pressure coefficient C_p comparison is shown for the baseline NACA 4415 airfoil and modified airfoil CFJ4415-005-085 with $C_\mu = 0.1$ at an angle of attack $= 20^\circ$. In the case of CFJ4415-005-085, a flow separation on the blowing and the suction becomes visible at their location. Figure 12 demonstrates that the pressure change near the leading edge is significant, and that blowing near the leading edge influences the low-pressure area of the upper surface more effectively than downstream suction. When the C_p is calculated on discontinuous wall surfaces at the blowing point, an overpressure peak appears, indicating a substantial energy transfer between the blowing and main flow particles, which energizes the wall's boundary layer. Also, a peak of depression is observed at the level of the aspiration indicating the removal of the separation bubble. The distributions of the pressure coefficients C_p for the CFJ4415-005-085 airfoils with different values of C_μ ranging from 0.1 up to 0.4 in the case of an angle of attack $AoA = 20^\circ$ are illustrated in Fig. 13. The

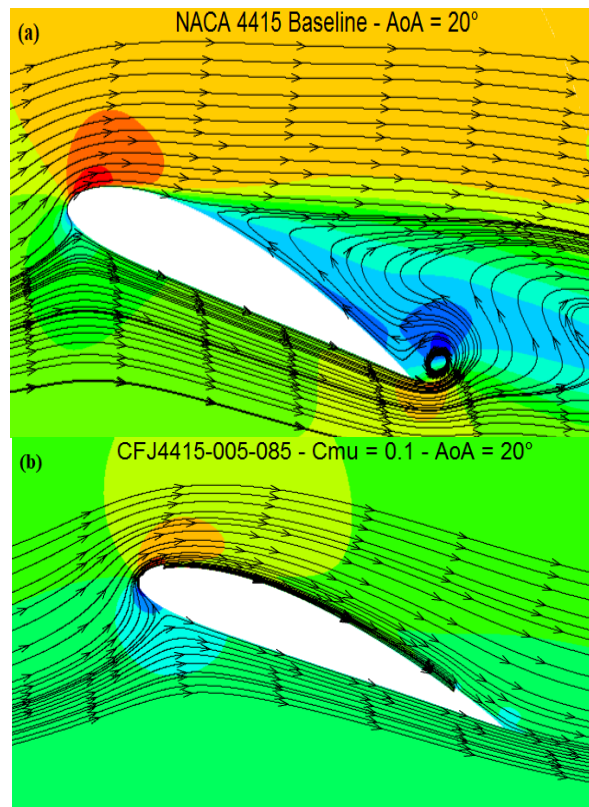


Fig. 14: Effect of blowing and suction on the separation bubble on the airfoil.

increase in C_μ causes super-suction at the leading edge of the modified airfoil, resulting in a very low-pressure value, as indicated by the high peak value of 4.8 to 10 for C_p . Note that the two peaks of overpressure and depression are steeper with the increase in C_μ , which justifies the size of the C_p lower surface for larger C_μ values.

In order to demonstrate more clearly the physics of control with CFJ, an airfoil CFJ4415-005-085 and with a $C_\mu = 0.1$ is compared to basic airfoil NACA 4415 at an incidence $AoA = 20^\circ$. The streamlines around the baseline NACA 4415 airfoil show in Fig. 14a the presence of a very considerable separation bubble in the vicinity of the upper part of the trailing edge. When the blowing and the suction are activated, favorable role of an airfoil with CFJ is clearly visible in Fig. 14b, the separation bubble is completely dissipated.

Figure 15 shows the velocity field around a modified airfoil NACA 4415-005-085 and $C_\mu = 0.4$ with an angle of attack $AoA = 40^\circ$. On the upper section of the airfoil, the blowing jet forms a region of entrainment, which is characterized by zones of overspeed relative to the velocity of the main flow. Figure 16 shows a zoomed portion of the blowing slot where a turbulent mixture layer between the blowing and the main flow is developed from the position of the blowing. This energizes the boundary layer of the wall and hence improves circulation, resulting in a lift gain. As a result, a depression develops, resulting in an increase in lift. Any increase in the C_μ parameter, on the other hand, creates a suction on the airfoil's upper surface, promoting the reattachment of the boundary layer. Finally, the CFJ airfoil improves air movement in the boundary layer region, which aids in the generation of higher lift and minimizes flow separation, hence boosting stall margin.

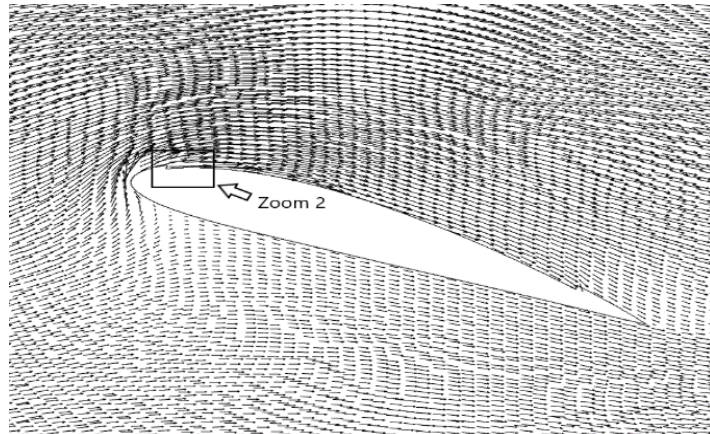


Fig. 15: Velocity vector around CFJ4415-005-085 at $AoA = 40^\circ$.

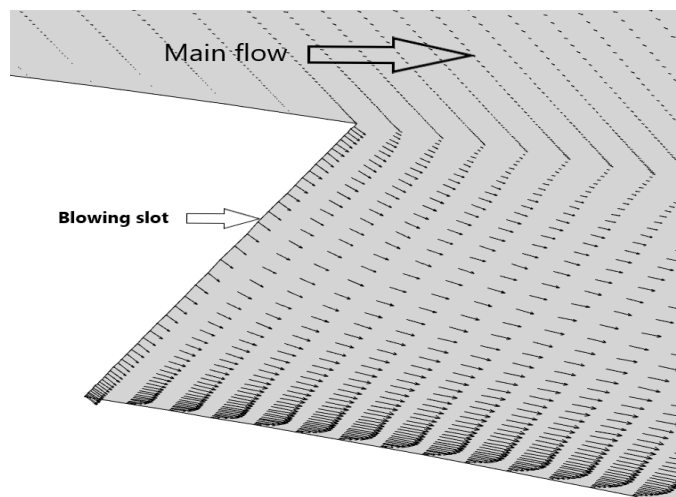


Fig. 16: Velocity vector near blowing slot.

6 CONCLUSION

The methods for maximizing lift applying CFJ control are numerically studied in this paper. An output slot near the leading edge and an inlet slot near the trailing edge generate the blowing and suction over NACA 4415 airfoil, where air is then recirculated. However, three airfoil geometries are created and depending on the blowing location: $X/C = 5, 10$, and 15% . In all of the cases analyzed, a fixed point of the suction was obtained at 85% of the chord. The blowing and suction produce a jet of the same intensity, with a momentum coefficient C_μ ranging from 0.1 to 0.4 .

As a result, when compared to the baseline airfoil, the lift coefficients of the modified airfoils show very promising results. Concerning the increase in lift, two conclusions may be noted: when the blowing location is near to the leading edge and when the momentum coefficient is high. As a conclusion, a correlation was performed in order to produce an expression for the maximum value of the lift coefficient that incorporates the momentum coefficient and the blowing position both at the same time. With minimum errors, the $CL_{\max}$ values determined in this present study demonstrate the validity of this correlation. However, to make this correlation more universal, additional parameter as airfoil thickness, Reynolds number, and suction location should be included in its formulation. So as a result, this correlation can only be applied to the modified airfoils employed in the study.

In conclusion, the airfoil with CFJ promotes movement of air in the boundary layer region, which aids in the creation of higher lift, reduces flow separation, thus increasing stall margin.

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