A Novel Airfoil Circulation Augment Flow Control Method Using Co-Flow Jet

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Abstract

A novel subsonic airfoil circulation augment technique using co-flow jet(CFJ) to achieve superior aerodynamic performance for subsonic aircraft is proved numerically by CFD simulation. The advantages of co-flow jet airfoil include high lift at high angle of attack, ultra high C_l/C_d at cruise point, and low penalty to the overall cycle efficiency of the airframe-propulsion system.

Unlike the conventional circulation control (CC) airfoil which is only suitable for landing and taking off, the CFJ airfoil can be used for the whole flying mission. No blunt leading and trailing edge is required so that the pressure drag is small. No moving parts are needed and make it easy to be implemented and weight less. The jet to enhance the circulation will be recirculated. Compared with the CC airfoil, the recirculating CFJ airfoil will significantly save fuel consumption because: 1) the power required to energize the jet is less; 2) no penalty to the jet engine thrust and efficiency due to the disposed jet mass flow since the jet mass flow is recirculated.

For the NACA2415 airfoil studied, at low AOA with moderate momentum jet coefficient, the coflow jet airfoil will not only significantly enhance the lift, but also dramatically reduce the drag, or even generate the negative drag (thrust). The mechanism is that the coflow jet can control the pressure drag by filling the wake, and could generate negative pressure drag greater than the friction drag. This may allow the aircraft to cruise with very high aerodynamic efficiency. At high AOA, both the lift and the drag are significantly higher than the airfoil with no flow control, which may enhance the performance of taking off and landing within short distance.

1 Introduction

To achieve high performance aircraft design, revolutionary technology advancement should be pursued to dramatically reduce the weight of aircraft and fuel consumption, significantly increase aircraft mission payload and maneuverability. Both the military and commercial aircraft will benefit from the same technology. As an effort toward these goals, this paper suggests a novel flow

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control technique to achieve high aerodynamic performance, i.e., high lift at high AOA, high C_l/C_d at cruise point, and low penalty to the overall cycle efficiency of the airframe-propulsion system.

Flow control is playing a more and more important role to improve aircraft aerodynamic performance[1][2]. To enhance lift and suppress separation, various flow control techniques have been used including rotating cylinder at leading and trailing edge[3][4][2], circulation control using tangential blowing at leading edge and trailing edge[5][6] [7][8][9][10], multi-element airfoils[11][12], pulsed jet separation control[13][14][15], etc. The different flow control methods have their different features. For example, the rotating cylinder and circulation control are generally most effective when the leading edge or trailing edge are thick. The multi-element airfoil can generate very high lift, but generally comes with large drag penalty.

In the summer of 2002, the joint research team from University of Miami(UM) and AFRL studied a new flow control concept for aircraft engine compressor blades: using co-flow wall jet on the suction surface to enhance the compressor cascade diffusion[16, 17]. Based on the CFD simulation, a very large diffusion factor, 0.965, is achieved. The diffusion factor reaches the limit of the geometry and is far greater than the current upper limit of 0.65. This paper applies the new flow control technique of the coflow jet cascade to high lift airfoil since both experience severe adverse pressure gradient at high loading.

Unlike the conventional circulation control airfoils, for which the jets are mostly implemented at leading and trailing edge, the co-flow jet (CFJ) airfoil is implemented on the majority area of the suction surface of the airfoil. The co-flow jet airfoil is to open a long slot on the airfoil suction surface from near leading edge to near trailing edge(see fig.1). A high energy jet is then injected near the leading edge tangentially and the same amount of mass flow is sucked away near the trailing edge. The turbulent shear layer between the main flow and the jet causes a strong turbulence diffusion and mixing, which enhance the lateral transport of energy and allow the main flow to overcome the severe adverse pressure gradient and stay attached at high angel of attack(AOA). At a certain AOA, the airfoil always achieve a significantly higher lift due to the augmented circulation. The operating range of AOA, hence the stall margin, is also significantly increased. The coflow jet airfoil does not rely on the Coanda effect at the leading or trailing edge, and hence the thick leading or trailing edge are not required. The technique can apply to any type of airfoils including the modern high speed thin airfoil, and can be combined with other flow control techniques.

When a flow control technique for airfoil is developed , we have to consider the overall airframe-propulsion system to make sure that the benefit outweighs the penalty. For the proposed coflow jet airfoil, since the jet blows and sucks the same amount of the mass flow, the jet hence can be recirculated to reduce the energy expenditure of the overall airframe-propulsion system compared to the blowing only method such as the circulation control. The jet blowing flow is usually from the engine. For the blowing only method, the high energy jet is dumped out and that is a penalty to the engine efficiency since the engine needs to energize the flow from the low energy free stream. The jet has higher energy state than the free stream flow even near the trailing edge. Hence less work needs to be done to energize the flow for blowing and the overall cycle efficiency can be higher. In addition to recirculating the jet flow, another energy saving of this flow control method is that it is desirable to blow the jet near leading edge where the pressure is low and to suck the jet near the trailing edge where the pressure is high.

Different from the conventional circulation control (CC) airfoil which may be most suitable for taking off and landing, the CFJ airfoil can be used for the whole flying mission from taking off, cruise, maneuver, to landing. No moving parts are needed and make it easy to be implemented and weight less. The CFJ airfoil does not require large leading edge(LE) or trailing edge(TE) and hence has small form drag as the regular modern airfoil.

A CC airfoil relies on local favorable pressure gradient on a curved surface to make the flow attached, the Coanda effect. Such favorable pressure gradient exists at the airfoil leading edge due to the suction and at the end of the trailing edge due to the low base pressure when the trailing edge is blunt. To make the CC airfoil effective, the blunt TE is hence needed, which is also the reason to create large drag at small AoA such as at cruise. At large AoA, because the mainflow can not resist the large adverse pressure gradient, the local TE favorable pressure gradient can not be achieved and hence the Coanda effect is difficult to maintain. If only TE blowing is used, the CC airfoil will usually stall at smaller AoA than the non-CC airfoil with sharp TE[18]. The CFJ airfoil significantly increase the AoA range and hence increase the safety margin of the aircraft. Above limitations of the CC airfoil may be part of the reasons that the CC airfoil has not been used for realistic aircraft so far.

For the CFJ airfoil, when the AOA is not large such as at cruising point, the pressure gradient may not be very severe. When the co-flow jet is used to enhance the lift, the mainflow around the airfoil is energized and the wake is filled to have a shallow defect shape or even protruding shape. This will reduce the drag or generate thrust (negative drag) for the airfoil. Obviously, there may be an optimum jet control to be most energy efficient. For example, it may be the optimum to achieve zero drag instead of the negative drag (thrust) because the airfoil may not be an efficient propulsion system. The filled wake will generate low noise level since there is no wake mixing. The noise level could be lower than the CC airfoil which has little wake filling effect. The enhanced lift can reduce the wing span for easy storage and reduced wet area and skin friction. The enhanced lift can also significantly shorten the taking off and landing distance. Basically, we can effectively trade the thrust to lift through CFJ at short landing and taking off without using vectored device. The special mechanism of the CFJ airfoil makes it workable for the full flying envelop.

In summary, the new flow control method proposed in this paper appears to have the following advantages: 1) It is effective to enhance lift and suppress separation. It can achieve extremely high C_l/C_d (infinity when $Cd = 0$) at low AOA(cruise), and very high lift and drag at high AOA(taking off and landing).; 2) It significantly increases the AOA operating range and stall margin; 3) It is energy efficient for the overall airframe-propulsion system; 4) It can be applied to any airfoil, thick or thin.

Above advantages of the CFJ airfoil may derive the following superior aircraft performance: 1) The CFJ airfoil works for the whole flying mission instead of only taking off and landing; 2) Economic fuel consumption; 3) Short distance taking off and landing; 4) No moving parts are needed and the implementation is not difficult; 5) Small wing span for easy storage, light weight and reduced skin friction; 6) Low noise since no high lift flap system is used; 7) The CFJ airfoil can be used for low and high speed aircraft.

The wind tunnel tests are currently in progress under the support of NASA Langley Research Center.

2 Results and Discussion

Fig.1 shows the baseline airfoil, NACA2415, and the airfoil with co-flow jet slot. The chord length is 0.3m. The coflow jet airfoil is modified from the baseline airfoil by translating the suction surface vertically lower by 1.67% of the chord. The slot surface shape is exactly the same as the original baseline airofil suction surface . The slot inlet and exit are located at 6.72% and 88.72% of the chord from the leading edge. The slot inlet and exit faces are normal to the slot surface to ensure that the jet will be tangential to the main flow. The slot inlet and exit area are 1.56% and 1.63% of the chord.

The Fluent CFD software is used as the tool to simulate the airfoil flows in this study. The mean flow governing equations are the 2D compressible Navier-Stokes equations. The O-mesh is used as shown in Fig.2. The $k - \epsilon$ turbulence model with wall function is used to save CPU time. The solutions of two typical cases are compared with the solutions using $k - \epsilon$ model integrating to the wall. The results have little difference. The full turbulent boundary layer assumption is used since the CFD solver does not have a transition model. Very fine mesh is used to achieve mesh independent solutions. A rectangular farfield boundary is used with the downstream boundary extended to 30 chord length, upstream, lower and upper boundary to 20 chord length. The freestream Mach number is 0.3 and the Reynolds number is 1.9×10^6. For all the computation, the jet inlet holds a constant total pressure equal to $1.315Pt_{freestream}$. The jet exit static pressure is iterated to match the jet inlet mass flow rate.

2.1 CFJ Airfoil Performance

Fig.3 is the lift coefficient vs angle of attack (AOA) for the baseline airfoil and the coflow jet airfoil. For the baseline airfoil, the lift coefficient predicted by CFD agrees excellently with the experiment results at $Re = 3 \times 10^6$[19] before stall. CFD predicts a little delayed stall and higher lift coefficient in the stall region. Fig.3 indicates that the lift of the coflow jet airfoil is increased significantly. The zero lift AOA for the baseline airfoil is $-2°$, and is $-6°$ for the coflow jet airfoil. The stall AOA is increased by 2°. Hence the operating range of AOA is increased totally by 38%. The peak lift value is increased by 80%, which is the minimum lift increase. When the AOA is decreased, the lift increase is greater. For example, at AOA= 2°, the lift increase is 250%.

Fig. 4 shows the streamlines at AOA=20°. The baseline airfoil has a massive separation, while the coflow jet airfoil flow is nicely attached. The attached flow is mainly due to the turbulent mixing[16], which transfers energy from the jet to the main flow so that the main flow can overcome the severe pressure gradient to stay attached.

Fig. 5 is the isentropic Mach number distribution on the surface of the airfoil at AOA=20°. It shows that the coflow jet airfoil creates a very strong suction effect near the leading edge and the flow is accelerated from the freestream Mach number 0.3 to the peak Mach number 1.7. The peak Mach number of the baseline airfoil is about 0.9. However, the baseline airfoil can not sustain the severe pressure gradient and the massive separation yield small loading on the aft portion of the airfoil. The coflow jet airfoil has much higher acceleration and diffusion on the suction surface and stronger deceleration on the pressure surface, which result in higher lift and circulation. Fig. 5 also shows that the leading edge stagnation point of the coflow jet airfoil is located more downstream than that of the baseline airfoil due to the higher circulation. The first spikes near the leading edge is due to the coflow jet injection which accelerates the flow on suction surface due to the mixing. The shape of the spike is not necessarily accurate and may be created by the numerical boundary condition treatment. The second spike near the trailing edge is due to the low pressure suction at the jet exit.

Fig.6 is the Mach number contours in the leading edge region at AoA=20° for the baseline and the CFJ airfoil. It shows that the CFJ airfoil has a local supersonic region. The high energy jet mixes with the mainflow through a low momentum wake.

In this study, while the AOA varies, the coflow jet inlet total pressure is held constant to simulate a passive flow control. At different AOA, the main flow will have different static pressure at the location of the jet inlet, which determines the mass flow rate of the jet and the jet injection velocity. Hence the jet momentum coefficient varies with AOA. The jet momentum coefficient based on the conventional definition is:

$$C_\mu = \frac{\dot{m}_j V_j}{0.5\rho_\infty U_\infty^2 S} \tag{1}$$

Fig. 7 shows the variation of C_μ vs AoA. When AoA varies from -8° to 22°, C_μ increases from 0.15 to 0.25.

Fig.8 is the drag polar for the baseline airfoil and the coflow jet airfoil. When AOA is high, both the lift and drag of the coflow jet airfoil is significantly higher than the baseline airfoil. Compare the peak lift points for both airfoils, the drag of the coflow jet airfoil is 160% higher than that of the baseline airfoil. However, when AOA$< 4^\circ$, the lift of the coflow jet airfoil is significantly higher and the drag is significantly lower than that of the baseline airfoil. When AOA$< 0^\circ$, the lift coefficient is still very large($C_l = 0.862$ at AOA=0°, see fig.3), but the drag becomes negative(thrust). At AOA=0°, the C_l/Cd=2224.

The drag of an airfoil is contributed from two sources, friction drag and pressure drag(form drag). The friction drag will always be in the opposite direction of the flight, that is, always positive. The negative drag hence must be from the pressure drag. This can be seen from fig.9, which shows the friction drag, pressure drag and total drag for the coflow airfoil respectively. Fig.9 indicates that the friction drag is fairly constant and decreases slightly near stall. However, the pressure drag varies largely. The pressure drag is the dominant contribution to the total drag near stall. When AOA is decreased, the pressure drag also decreases monotonically. When AOA$< 4^\circ$, the pressure drag becomes negative and the total drag is reduced to negative when AOA$< 0^\circ$.

Fig.10 is the drag distribution of the baseline airfoil. Similar to the coflow airfoil, the friction drag is also fairly constant compared with the pressure drag. The pressure drag decreases when the AOA is decreased from the stall region. However, the pressure drag increases when the decreasing AOA passes the zero lift point and does not become negative.

The negative drag can also be explained from the the control volume point of view. The high velocity jet will transfer the kinetic energy to the main flow due to the turbulent mixing. When the AOA is not large, the diffusion is not severe. The main flow on the suction surface has the large streamwise velocity past the trailing edge so that the streamwise velocity in the wake region is greater than the freestream velocity. This can be seen in fig.11, which shows the wake shape of the two airfoils at one chord length downstream of the trailing edge. The wake of the baseline airfoil has the usual defect shape while the wake of the coflow airfoil has the protruding shape. Fig. 12 is the Mach number contours at the trailing edge region at AoA=0°. It shows that the high energy jet of the CFJ airfoil fill the wake and a thrust is created.

Based on the control volume analysis, the drag is determined by

$$D = \int\int \rho U(U_\infty - U)dA \tag{2}$$

Where U is the wake velocity.

When U is greater than U_∞, the drag is negative and becomes thrust. When the AOA is very large, the jet energy is mostly used to diffuse the flow to make the flow attached. For the current study with the constant jet inlet total pressure of $1.35Pt_{freestream}$ at AoA=20°, the coflow jet does not provide enough energy to the main flow and the wake is very large. The pressure drag is hence overwhelming, which is desirable for short distance landing.

2.2 Energy Expenditure

The power required to energize jet is determined by the total pressure ratio between the jet exit and jet inlet. For CC airfoil which has blowing only, the jet inlet is the free stream. For the recirculating CFJ airfoil, the jet inlet is the suction exit.

To compare the power required for the blowing only CC airfoil and the recirculating CFJ airfoil, we assume that the jet mass flow rate is the same. Then the power ratio between the power required by the recirculating CFJ airfoil and the CC airfoil is:

$$
\begin{aligned}
P_R &= \frac{P_{CFJ}}{P_{CC}} \\
&= \frac{\eta_{CC}}{\eta_{CFJ}} \frac{((P_{02}/P_{01})^{\frac{\gamma-1}{\gamma}} - 1)_{CFJ}}{((P_{02}/P_{01})^{\frac{\gamma-1}{\gamma}} - 1)_{CC}}
\end{aligned} \tag{3}
$$

Where η is the efficiency of the pumping system, P_{02} and P_{01} are the total pressure at the jet inlet and exit.

Fig. 13 is the total pressure ratio against momentum coefficient for blowing only and recirculating CFJ airfoil. The solid line is the total pressure ratio of 1.315 if blowing only is used. In this study, the injection total pressure is held constant. The variation of the momentum coefficient is due to the change of AoA. The dash line is the total pressure ratio if the jet is recirculated. Since the jet still has high momentum near the suction slot and the total pressure is still fairly high, it makes the total pressure ratio of the recirculating jet varying from 1.02 to 1.11, which is significantly lower than the blowing only total pressure ratio. Please note that this comparison does not include the extra flow loss in the ducts of the injection and suction.

Fig. 14 shows the ratio of the power required for recirculating the jet and the power for blowing only. If assume the pumping systems of the blowing only and recirculating jet have the same efficiency, the solid line in Fig. 14 is the power ratio with the maximum value about 0.35 at stall. If we make a very conservative assumption that the recirculating jet pump efficiency is only half of that of the blowing only system, the power ratio shown as the dash line in Fig. 14 is still significantly lower than 1.0 and varies from 0.15 to 0.75. This means that the recirculating jet will bring a significant energy expenditure saving compared with the CC airfoil.

The other penalty that the conventional CC airfoil brings to the propulsion system is the disposed jet mass flow, which will hurt the engine thrust and efficiency.

Assume a jet engine is used to power the aircraft, the engine is tested on the ground and the nozzle expand the flow to ambient pressure. The thrust of a jet engine is then determined by the momentum difference between the inlet and nozzle. On the ground the engine flying speed is zero and hence the thrust is expressed as:

$$F = m_{nozzle} V_{nozzle} \tag{4}$$

Eq.(4) means that the thrust decrease will be directly proportional to the mass flow dumped out if a blowing only CC airfoil is used. For a recirculating CFJ airfoil, this serious penalty is avoided.

The total efficiency of jet engine is:

$$\eta = \frac{V_\infty m_{nozzle}(V_{nozzle} - \frac{m_{nozzle}}{m_{inlet}} V_\infty)}{Q} \tag{5}$$

where the Q is the heat released form the combustion. If assume Q is the same, $\frac{m_{nozzle}}{m_{inlet}} \approx 1$, then η is proportional to m_{nozzle}. This means that the disposed jet flow will directly reduce the propulsion system efficiency.

In summary, compared with the CC airfoil, the recirculating CFJ airfoil will have 3 advantages to save energy expenditure: 1) the power required to energize the jet is less; 2) no penalty to the engine thrust due to the disposed jet mass flow; 3) no penalty to the engine efficiency due to the disposed jet mass flow;

Above advantages of the recirculating CFJ airfoil will be reflected as a significant benefit of fuel consumption saving. If the propulsion system for the aircraft is not a jet engine, above advantages will be equivalently transferred to other power system.

3 Work in Progress

The wind tunnel tests to prove this concept experimentally are in progress under the support of NASA Langley Research Center.

4 Conclusions

A novel subsonic airfoil flow control technique using co-flow jet to achieve superior aerodynamic performance for subsonic aircraft is proved numerically by CFD simulation.

The co-flow jet airfoil is to open a long slot on the airfoil suction surface from near leading edge to near trailing edge. A high energy jet is then injected near the leading edge tangentially and the same amount of mass flow is sucked away near the trailing edge. The jet hence can be recirculated to reduce the energy expenditure of the overall airframe-propulsion system than blowing only. The turbulent shear layer between the main flow and the jet causes a strong turbulence diffusion and mixing, which enhance the lateral transport of energy and allow the main flow to overcome the severe adverse pressure gradient and stay attached at high angel of attack(AOA). The coflow jet airfoil achieves significantly higher lift due to the augmented circulation. The airfoil does not rely on the Coanda effect at the leading or trailing edge. Hence the technique can apply to modern high speed thin airfoil, and can be combined with other flow control techniques.

The new flow control method suggested in this paper appears to have the following advantages: 1) It is an effective method to enhance lift and suppress separation. It can achieve extremely high C_l/C_d at low AOA(cruise), and very high lift and drag at high AOA(taking off and landing).; 2)

It significantly increases the AOA operating range and stall margin; 3) It is energy efficient for the overall airframe-propulsion system; 4) It has little geometric limitation and generally can be applied to any airfoil, thick or thin.

Compared with the CC airfoil the recirculating CFJ airfoil will significantly save fuel consumption because: 1) the power required to energize the jet is less; 2) no penalty to the jet engine thrust and efficiency since the jet mass flow is not disposed.

Above advantages of the CFJ airfoil may derive the following superior aircraft performance: 1) The CFJ airfoil works for the whole flying mission instead of only taking off and landing; 2) Economic fuel consumption; 3) Short distance taking off and landing; 4) No moving parts are needed and the implementation is not difficult; 5) Small wing span for easy storage, light weight and reduced skin friction; 6) Low noise since no high lift flap system is used; 7) The CFJ airfoil can be used for low and high speed aircraft.

For the NACA2415 airfoil studied, at low AOA with moderate momentum jet coefficient, the coflow jet airfoil will not only significantly enhance the lift, but also dramatically reduce the drag, or even generate the negative drag (thrust). The mechanism is that the coflow jet can control the pressure drag by filling the wake, and could generate negative pressure drag greater than the friction drag. This may allow the aircraft to cruise with very high aerodynamic efficiency. At high AOA, both the lift and the drag are significantly higher than the airfoil with no flow control, which may enhance the performance of taking off or landing within short distance.

5 Acknowledgment

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References

[1] M. Gad-el Hak, "Flow Control: The Future ," *Journal of Aircraft*, vol. 38, pp. 402–418, 2001.

[2] M. Gad-el Hak, *Flow Control, Passive, Active, and Reactive Flow Management*. Cambridge University Press, 2000.

[3] V. Modi, M. Fernando, and T. Yokomizo, "Drag Reduction of Bluff Bodies Through Moving Surface Boundary Layer Control." AIAA Paper No. 90-0298, 1990.

[4] D. Cichy, J. Harris, and J. MacKay, "Flight Tests of a Rotating Cylinder Flap on a North American Rockwell YOV-10A Aircraft." NASA CR-2135, 1972.

[5] L. C. Bradley, "An Experimental Investigation of A Sting-Mounted Finite Circulation Control Wing." M.S. Thesis, Air Force Institute of Technology, 1995.

[6] N. Wood, L. Robert, and Z. Celik, "Control of Asymmetric Vortical Flows over Delta Wings at High Angle of Attack," *Journal of Aircraft*, vol. 27, pp. 429–435, 1990.

[7] N. Wood and L. Robert, "Control of Vortical Lift on Delta Wings by Tangential Leading-Edge Blowing," *Journal of Aircraft*, vol. 25, pp. 236–243, 1988.

[8] N. Wood and J. Nielsen, "Circulation Control Airfoils-Past, Present, Future." AIAA Paper 85-0204, 1985.

[9] R. J. Englar, L. A. Trobaugh, and R. Hemmersly, "STOL Potential of the Circulation Control Wing for High-Performance Aircraft," *Journal of Aircraft*, vol. 14, pp. 175–181, 1978.

[10] R. J. Englar, "Circulation Control for High Lift and Drag Generation on STOL Aircraft," *Journal of Aircraft*, vol. 12, pp. 457–463, 1975.

[11] A. Smith, "High-Lift Aerodynamics," *Journal of Aircraft*, vol. 12, pp. 501–530, 1975.

[12] J. Lin, S. Robinson, R. McGhee, and W. Valarezo, "Separation Control on High Reynolds Number Multi-Element Airfoils." AIAA Paper 92-2636, 1992.

[13] K. McManus and J. Magill, "Airfoil Performance Enhancement Using Pulsed Jet Separation Control." AIAA Paper 97-1971, 1997.

[14] K. McManus and J. Magill, "Separation Control in Incompressible and Compressible Flows Using Pulsed Jets." AIAA Paper 96-1948, 1996.

[15] H. Johari and K. McManus, "Visulation of Pulsed Vortex Generator Jets for Active Control of Boundary Layer Separation." AIAA Paper 97-2021, 1997.

[16] G.-C. Zha, (team members: David Car, and W. Copenhaver), "Super Diffusion Cascades Using Co-Flow Jet Flow Control." National Research Council Summer Faculty Final Report, Aug. 23, 2002.

[17] D. Car, N. J. Kuprowicz, J. Estevadeordal, G.-C. Zha, and W. Copenhaver, "Stator Diffusion Enhancement Using A Re-circulating Co-flowing steady Jet." ASME GT-2004-53086, ASME TURBO EXPO 2004, June 14-17, 2004.

[18] Y. Liu, L. N. Sankar, R. J. Englar, K. K. Ahuja, and R. Gaeta, "Computational Evaluation of the Steady and Pulsed Jet Effects on the Performance of a Circulation Control Wing Section." AIAA Paper 2004-0056, 42nd AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada 5 - 8 Jan 2004.

[19] J. Anderson, J.D., *Introduction to Flight, 4th edition.* McGraw-Hill Higher Education, 2000.

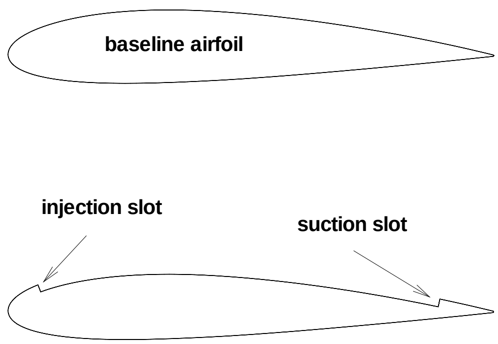

Figure 1: Baseline airfoil NACA2415 and the airfoil with co-flow jet slot.

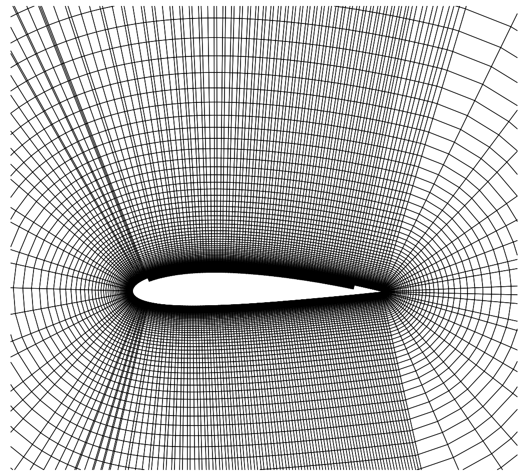

Figure 2: Mesh around the airfoil with co-flow slot.

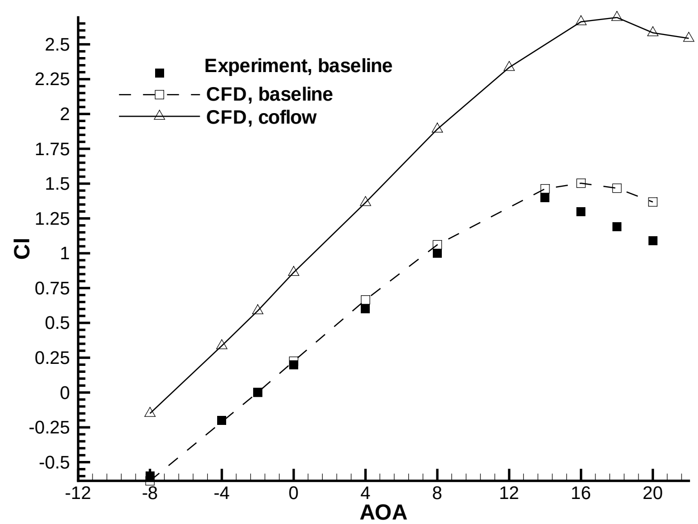

Figure 3: Lift coefficient vs angle of attack.

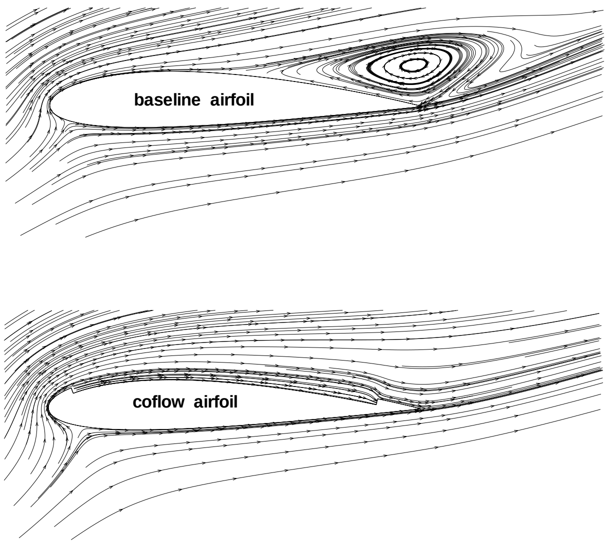

Figure 4: Streamlines at angle of attack of 20 degree.

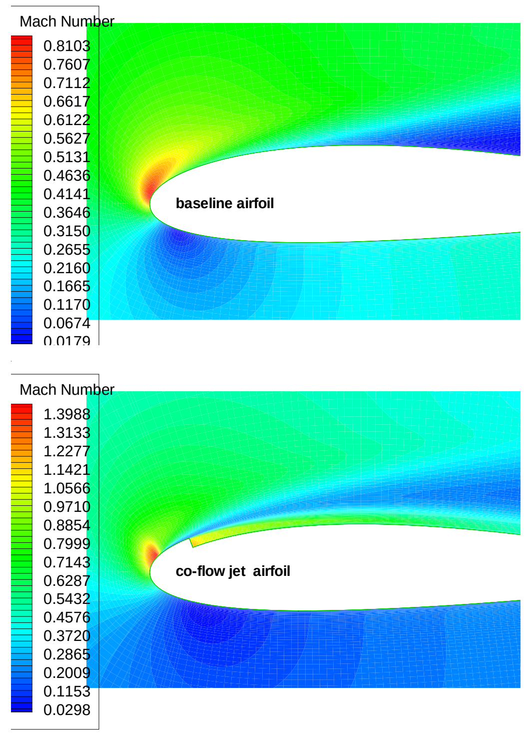

Figure 6: Mach number contours at AoA= 20° for the baseline and coflow jet airfoil.

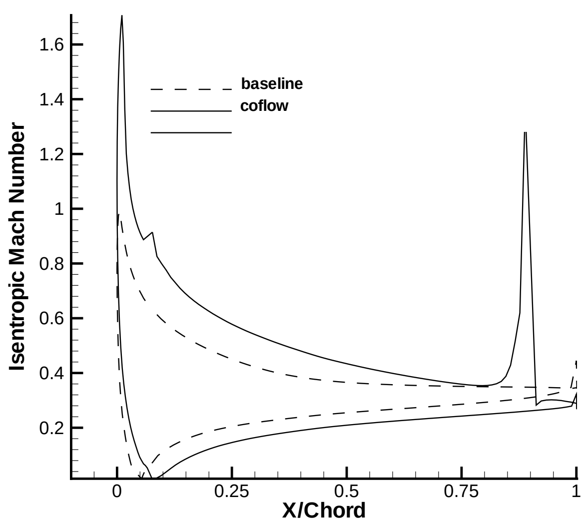

Figure 5: Surface isentropic Mach number distribution at angle of attack of 20 degree.

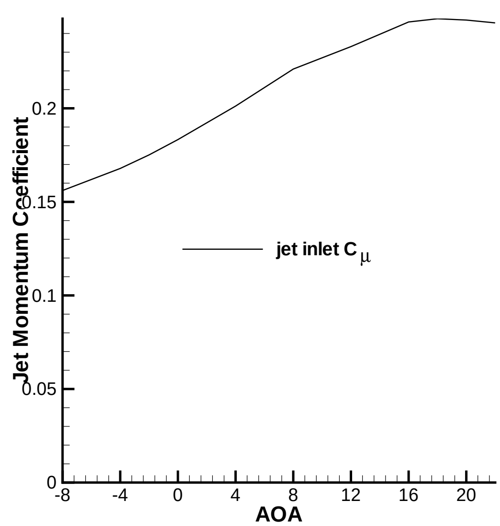

Figure 7: Jet momentum coefficient and equivalent momentum coefficient.

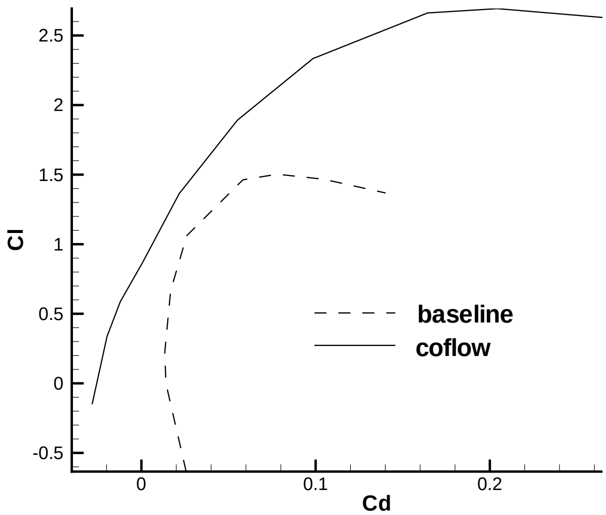

Figure 8: Drag polar for the baseline and coflow jet airfoil.

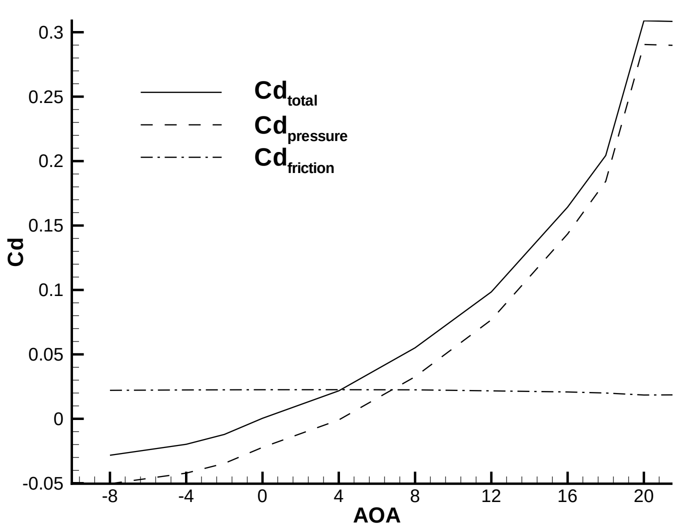

Figure 9: Calculated drag coefficients vs angle of attack for coflow jet airfoil.

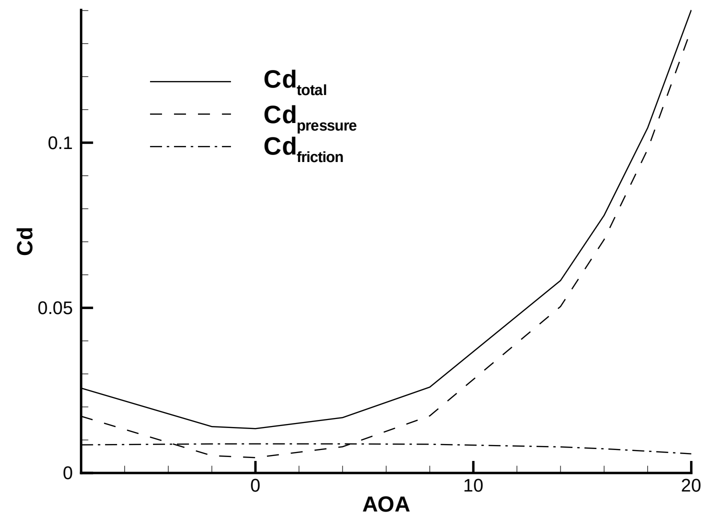

Figure 10: Calculated drag coefficients vs angle of attack for baseline airfoil.

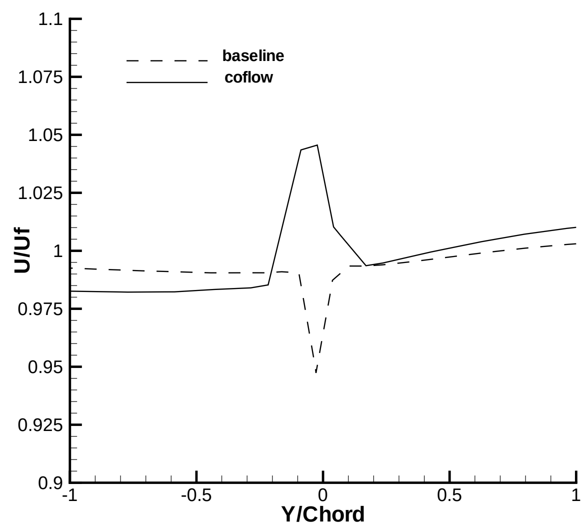

Figure 11: Wake shape for the baseline and coflow jet airfoil.

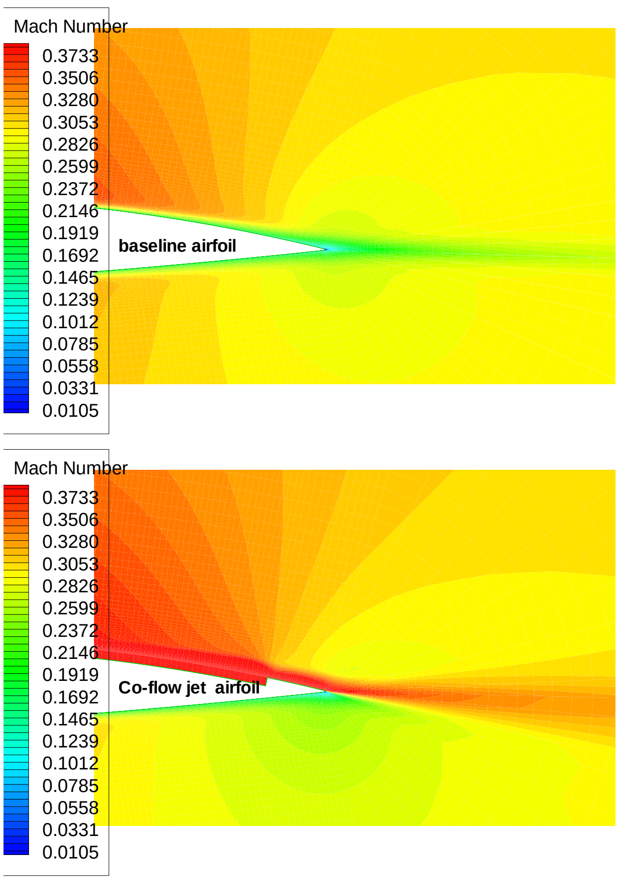

Figure 12: Wake Mach number contours at AoA=0.0° for the baseline and coflow jet airfoil

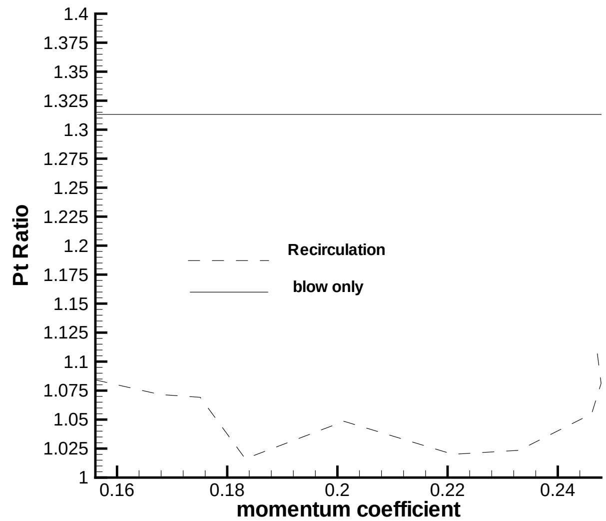

Figure 13: Total pressure ratio vs momentum coefficient for recirculating jet and blowing only.

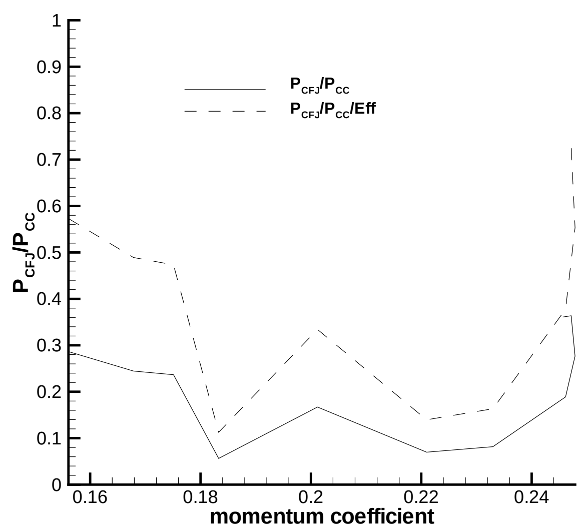

Figure 14: The ratio of the power required for jet injection for recirculating jet and blowing only.