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Co-Flow Jet (CFJ) Airfoils Practicality in Engineless Airplanes

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Practicality in Engineless Airplanes

By

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ABSTRACT

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This paper investigates the co-flow jet (CFJ) airfoils ability to further current aviation designs to be more environmental. With high cost and large contribution to carbon footprints, aeronautical designers look to drag reduction to decrease dependencies on fuel. Primary research on CFJ airfoils is led by Dr. Zha at the University of Maiami. Through various forms of analysis, CFJ airfoils use a jet stream to create movement of air in the boundary layer region that helps create more lift, reduce flow seperation therby increasing stall margin, and creates a thrust force. However, with further investigation, the magnitude of thrust created by CFJ components does not have sufficient evidence of enough force for a large commerical sized airplane, espically with takeoff. To definitely determine the possibiliteis for CFJ airfoil technology, more research will be needed. So far, pracitcal applications of CFJ can better improve current glider technologies, for companies like NASA and Airbus, and better egine integration for typical planes.

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INTRODUCTION

This paper discusses the emergence of engineless planes, modern high-altitude gliders, and the emergence of co-flow jet (CFJ) airfoils. It will explore the potential for CFJ airfoil applications and their potential to improve the aeronautical field for advancements in economics, health and safety, and environmental/sustainable practices.

With the growth in aircraft fleets and traffic and the current problem of global warming from noxious gases like carbon dioxide, the aeronautical industry needs to improve fuel efficiency through technological advancements. Globally, within the next 20 years, aircraft production will double to account for the increase in passengers and emerging economies [1]. This increase will lead to more air travel emissions which currently contribute an estimated 5% to global warming, based off fuel consumption. Although often forgotten, air travel is a big contributor to individuals' carbon footprints. For example, one round-trip flight across the US, from New York to San Francisco, contributes 2-3 tons to the average Americans' 19 tons of CO_2 emissions per year [2]. The future of aeronautics lies in the sector's ability to improve fuel efficiencies, for economic improvements and the future of the environment.

This paper will review the history and current use of engineless airplanes and review pertinent fluid dynamics so readers have a better sense of how to evaluate new aeronautical developments. Engineless airplanes, today, are primarily known as gliders whose design dates to WWII. Since then, these types of planes have grown more complicated with advanced gliders such as Airbus' Perlan Project or NASA's Prandtl Project. Using fluid dynamics, great leaps in engineering design have been possible.

This paper will review CFJ airfoils for their variances from baseline airfoils and application limitations. CFJ airfoils differ from typical airfoils because their geometry creates an abnormal thrust force. However, this paper will examine if CFJ airfoil's thrust capabilities can produce "engineless" commercial planes or if they are better suited for improvements in glider designs.

BACKGROUND

Historical and Current Applications

War often propels scientific discoveries. This was true for the origins of engineless planes. After WWI with the Versailles Treaty, the Ally powers attempted to limit Germany's ability to go to war again by restricting Germany's military and aviation as post-war punishments. For example, Germany was only allowed to have 100 unarmed seaplanes, and one backup engine for each. These limitations helped lead to progress in rocketry and motorless aircrafts [2]. Starting around 1923, the "Germans wanted to fly…high, long, and fast [and i]f they were not to be allowed engines to make that happen, then they would begin by creating new engineless aircraft[s] that could reach" these goals by advancing aerodynamics and structural knowledge of planes. The school of gliders came about through optimization of chord ratio, airfoil thinness, fuselage design, etc. to be able to improve lift and decrease induced drag [3]. Gliders are the main form of engineless airplanes today, and with further variations can lead to modern planes that take aviation to the next level, as described next.

Engineless airplanes have various applications, and are unique due to their high lift to drag ratios, along with their lack of an engine. Two high profile applications that are currently using a glider design are the Perlan Project, sponsored by Airbus, and NASA's Prandtl Project. The Perlan, shown in Figure 1, is designed to reach the stratosphere for weather and climate change testing, using mountain waves to reach record breaking heights. The project founded by Einar Enevoldson, has found success with the Perlan I reaching 17,000 ft into the stratosphere (just over 50,000 ft in the air). This was a new world record, and hence has been sponsored by Airbus to design and test the Perlan II with a goal of 90,000 ft [4]. These heights are reached by oscillations of air that are pushed over a crest of a mountain range that then causes waves that can "rise thousands of feet higher than the summit of the mountains" when in the right conditions. It has been theorized that these *right conditions* could create "narrow band[s] of winds with speeds greater than 260 mph…[and] allow mountain waves to propagate as high as 130,000 ft" [5]. Special steps in the design process are taken for optimal performance at that altitude, and in the discussion section this will be further detailed in accordance to CFJ applicability.

Figure 1: Airbus' Perlan project, top, founder in front of Perlan I, bottom, towing of Perlan I during preliminary test flights [5].

Another similar glider project, is NASA's Prandtl (or Preliminary Research Aerodynamic Design to Lower Drag) Project shown in Figure 2. This project has been investigating wing shapes and amplitude twisting to reduce drag and eliminate vertical tail needs. Preliminary research on the Prandtl shows increase in fuel economy by 30% and elimination of some control surfaces. NASA is focused on this design's use as a deployable UAV (unmanned aeronautical vehicle) on Mars to relay topographical images and data back to Earth. This small glider design, called the Prandtl-M, could help determine a suitable landing spot for future Mars explorations, while enabling easy deployment and little need for power due to the high lift glider design [6]. Projects like these need advancements in the glider field—where high lift to drag ratios are required with little need for propulsion. Advancements in airfoil shapes could help contribute to these projects, as well as, drones, and commercial airplane performances and this paper aims at exploring the application of such airfoil shapes for that purpose.

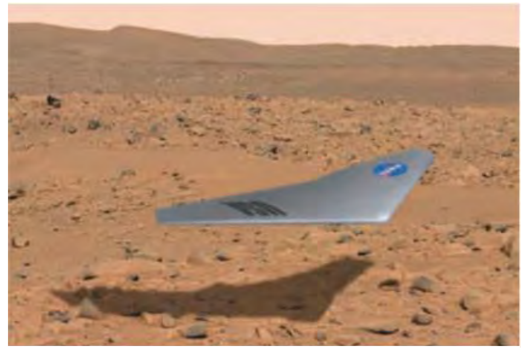


Figure 2: Depiction of NASA's Prandtl collecting data on Mars [6].

Fluids Background

To improve aeronautical design, the fundamentals of fluid dynamics are necessary to better understand the forces that act on a plane. A fluid's motion is described mathematically by using Naiver-Stokes (NS), equation 1.

$$\rho \frac{D\vec{V}}{Dt} = -\vec{\nabla} P + \rho \vec{g} + \mu \nabla^2 \vec{V} \tag{1}$$

The NS equation is complex and requires assumptions and approximations for specific solutions. For example, if viscous forces are negligible (irrotational and inviscid flow, or high Reynolds flow) the NS equation is simplified to Euler's equation as an approximate solution that assumes frictional forces of motion, or viscosity, is zero. For some flows this is a valid assumption, but for flow over a plane, viscous forces are responsible for the drag experienced on an aircraft [7].

At the beginning of the 20th century with the onset of aircraft design, the need to be able to accurately calculate drag and lift brought about Ludwig Prandtl's revolutionary boundary layer (BL) concept. As described in Prandtl's paper in 1905,

> While dealing with a flow, the latter divides into two parts interacting on each other; on one side we have the "free fluid," which [is] dealt with as if it were frictionless…and on the other side the transition [or boundary] layer near the solid wall. The motion of these layers is regulated by the free fluid, but they for their part give to the free motion its characteristic feature by the emission of vortex sheets. [8]

This boundary layer, BL, is where a fluid interacts with a surface creating a shear-stress. Within this BL, shown as light blue in Figure 3, there is a large velocity gradient where viscosity cannot be neglected so a drag force is created. These velocity gradients are used in Prandtl's BL equations, equation 2, to quantify drag.

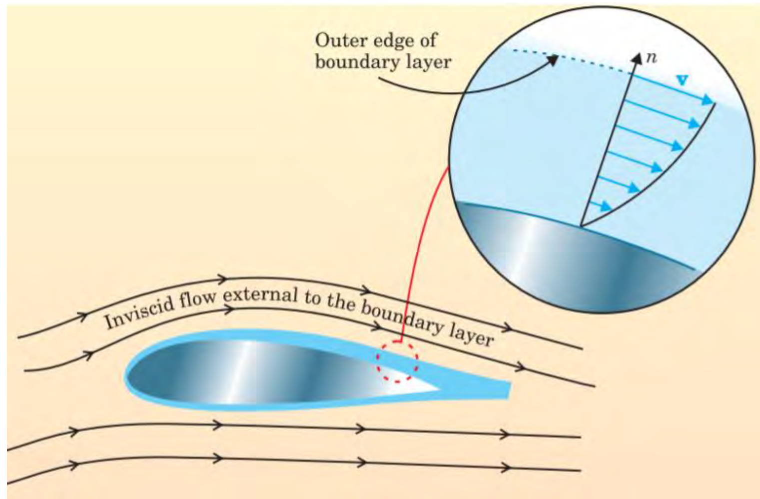


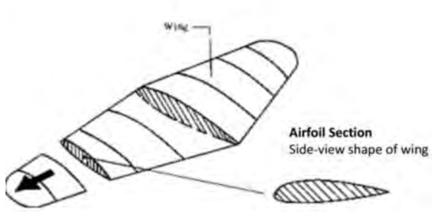
Figure 3: A fluid flow may be viewed as comprising two parts: 1) thin boundary layer (blue) adjacent to the surface, the effects of friction are dominant 2) flow outside boundary layer the flow is inviscid. Within the boundary layer there are velocity changes, as a function normal to distance n, from zero at surface to full inviscid flow at outer edge as shown in the blown-up bubble, top right [8].

$$u\frac{\delta u}{\delta x} + v\frac{\delta u}{\delta y} = U\frac{dU}{dx} + v\frac{\delta^2 u}{\delta y^2} \tag{2}$$

Due to the parabolic nature of this equation, compared to NS's elliptical behavior, solutions can be determined along the surface due to computational simplification [8]. This means drag can be solved for along any object of interest, like an airfoil, at various angles of attack versus the freestream flow (U).

A plane flies due to the large lift force created mainly by the airplane's wing. On an airfoil, there is low pressure on the top surface and high pressure on the lower surface, as shown by Figure 4.

A)



B)

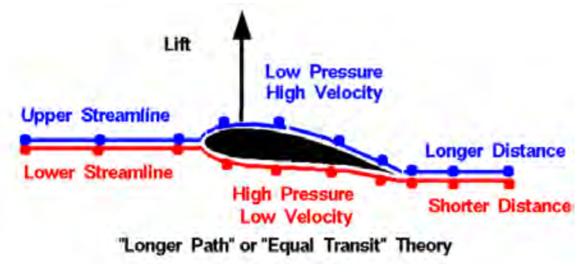


Figure 4: The airfoil shape that makes up a wing aerodynamic shape, shown in A, creates low pressure, high velocity region on top and a high pressure, low velocity region on the bottom, shown by B [9].

This change in pressure creates a force upwards on the wing, known as the lift force. These pressure differences are created by viscosity effects in the BL; that cause a starting vortex so air circulates around the airfoil creating higher velocities on the top versus the bottom of the airfoil. Based on Euler's (or Bernoulli's) equations, this equates to higher pressure on top and low pressure on the bottom of an airfoil. The flow pattern over an airfoil is depicted in Figure 5.

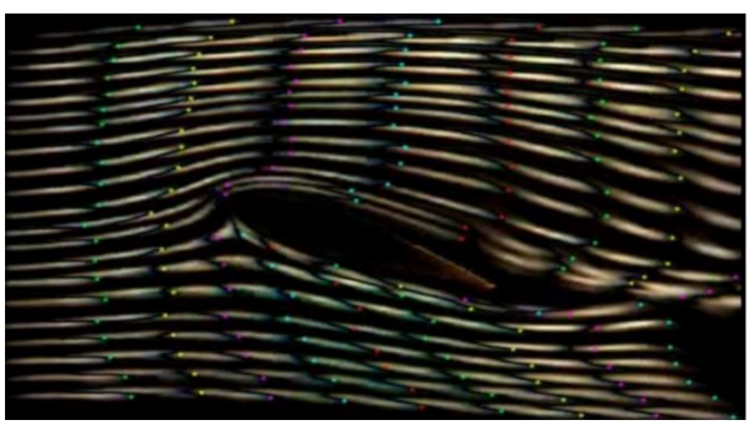


Figure 5: Shows how flow over the top of an airfoil moves faster than that below, since the colored dots are further along in the x-direction to the right. These streamlines also show how the fluid has a circulation to it [9].

A plane's lift force can be improved by changing the angle of attack (α) of the airfoil; the degree change from the airfoil's zero position in the xy-plane. As seen in Figure 5 and 6, the airfoil is angled positively upwards from the horizontal so it has a positive α. Through collect research[1], there are optimal angle of attack values for different airfoil shapes, that maximize lift force versus drag forces. At a certain point if the angle of attack becomes too large the BL separates from the surface of the airfoil, reducing lift and increasing drag, as shown in Figure 6. The drag force is combination of viscous forces tangential to freestream velocity (skin-friction drag) and pressure in the flow direction, or x-direction, (pressure drag). With flow separation both types of drag increase, thereby causing poor-aircraft performance [9]. As described by Pradtl:

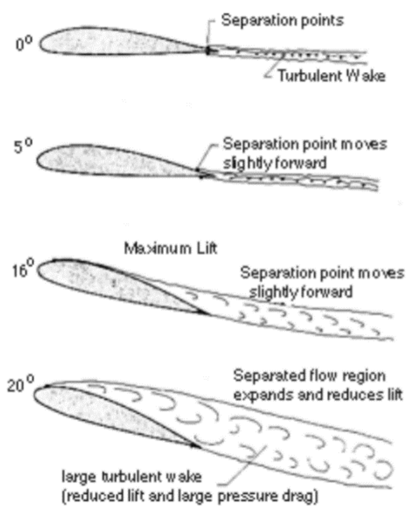


Figure 7: BL separation as angle of attack increases [9].

> [A]n increase of pressure, while the free fluid transforms part of its kinetic energy into potential energy, the transition layers instead, having lost a part of their kinetic energy (due to friction), have no longer a sufficient quantity to enable them to enter a field of higher pressure, and therefore turn aside from it. [8]

So, the separation of the BL occurs when an adverse pressure gradient occurs in the flow direction. When pressure is equal on top and bottom of the airfoil, a stall condition occurs where no lift force is created [8].

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[1] Data collected for various airfoils, showing how coefficient of lift and drag change at carious α-values can be found: http://airfoiltools.com/

The lift and drag can be calculated, and using lift coefficient (C_L) and drag coefficient (C_D) the equations can be simplified, as shown by equation 3 and 4. These coefficients are published values for specific airfoil shapes.

$$L = C_L \times \frac{\rho V^2}{2} A \quad (3)$$

$$D = C_D \times \frac{\rho V^2}{2} A \quad (4)$$

These equations use their respective coefficients and then density of fluid (ρ), velocity of main flow (V), and normal surface area (A) to the respective force. So, area for the lift is the area of wing's planform, and drag area is the entire wing's surface area. These two areas differ since lift acts in the normal y-axis, underneath the wing, while drag acts in direction of the air flow, normal x-axis, over entire wing. These fundamentals for understanding fluid motion around airfoils, are necessary to further design and improve upon current plane designs.

REVIEW OF CO-FLOW JET AIRFOILS

Decreases in drag reduces the required thrust from an engine and a plane's carbon emissions. A new research development called co-flow jet (CFJ) airfoils, have potential to produce their own thrust while decreasing drag for engineless aircraft applications. CFJ airfoils simplify aircraft design by integrating lift and propulsion, improving, like natural flight, performance and efficiency. Like a bird in flight, CFJ are to have zero drag for cruise and then negative drag to create trust for acceleration/take-off [10]. This kind of airfoil, as proposed by the authors of the papers, could push aviation to be engineless, relying on other forms of propulsion.

The CJF airfoil is mainly being researched at the University of Miami, with Dr. Zha in the green aviation department. The group has found CFJ components to improve a typical airfoil in three ways: 1) lift enhancement, 2) stall margin increase, and 3) drag reduction which leads to thrust generation. These are achieved with low energy expenditures. These CFJ components, compared to a typical airfoil, can be seen in Figure 7. The idea is that an air injection slot is added at the front portion of the wing, leading edge, and then a suction slot at the end portion of the wing, or trailing edge. These ports create an air jet stream over the top of the airfoil, which increases the adverse pressure gradient, at the airfoil's trailing edge. This mixing of the jet stream and main air flow, increases the flow's momentum seen over the top of an airfoil; causing a decrease in drag and larger α-values where the BL remains attached. In addition, the jet creates more circulation of air, further increasing the speed of air over the airfoil, so the lift force increases. A more detailed drawing of CFJ can be seen in Figure 8. The only similarity between typical airfoils to airfoils with CFJ components is induced drag created by tip vortices. However, a CFJ could render inefficient combustion engines, that lose 50% efficiency to thermal energy, to be needless, or at least less relied upon [10]. At the University of Miami,

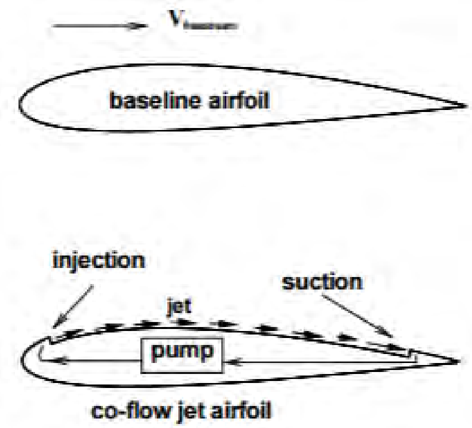

Figure 11:Top, baseline airfoil example (NACA2415) and bottom, the CFJ components on same baseline airfoil [10].

Figure 12:Top, baseline airfoil example (NACA2415) and bottom, the CFJ components on same baseline airfoil [10].

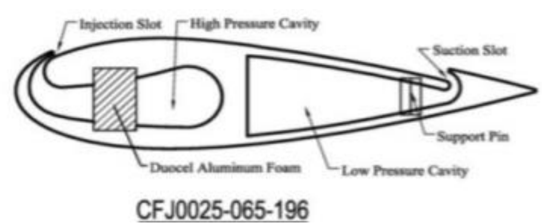

Figure 9: More detailed schematic of CFJ components with the jet flow [11].

various studies have been conduction on the application of these airfoils, using CFD and wind tunnels testing for analysis.

Derived expressions for lift and drag of a CFJ airfoil were found from NS, using control volume analysis by Zha et. al. If further interested, these derived equations can be found in [10] and were used by Zha et. al. to calculate pressure in the x,y-directions. From analysis work, the CFJ airfoil only experiences y-pressure drag, due to tip vortices.

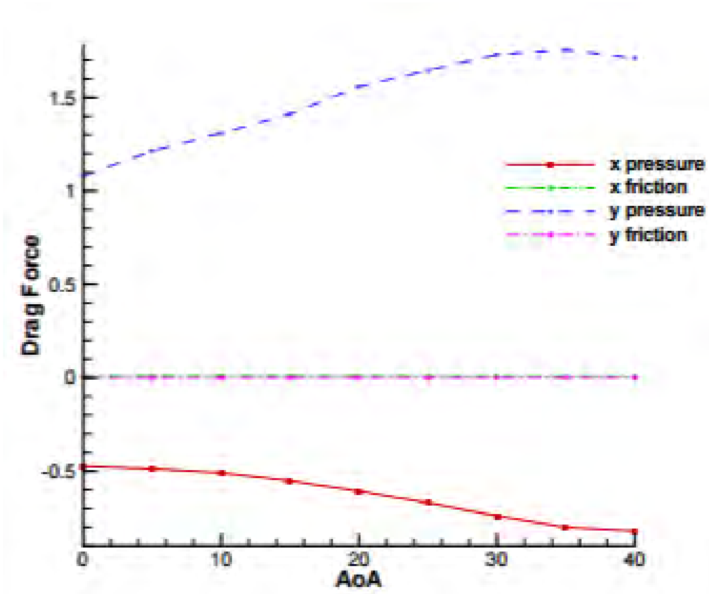

Figure 13: Drag breakdown at various angles of attack, of a NACA 6425 CFJ airfoil [10].

So, to decrease induced drag created by tip vortices, Zha et. al. picked a base airfoil with lower chamber. From there CFD analysis was conducted to analyzed all drag created, as shown by Figure 9. Shown in blue, the y-pressure or induced drag increases as α-values increase which is typical of airfoils at the flow separates. Shown in red, x-pressure collected was recorded as a negative value. This negative drag would be a force in the same direction as the plane's motion—so a thrust force. This shows variation from typical airfoils, where no force is produce in the direction of motion from the airfoil's shape and function. Further analyses, also, showed that lift with a CFJ improves in

comparison to the baseline airfoil shape. For a NACA 652-415 airfoil with CFJ components, at the point where slow separate occurred to high α-value, 88% more lift was seen when comparing the CFJ airfoil to baseline. A comparison between lift and increasing α for CFJ vs the baseline airfoil can be seen in Figure 10a. As shown, the lift coefficients for CFJ airfoils were consistently higher than the baseline at every α-value. When incorporating drag, by looking at ratio between coefficient of lift versus drag, the CFJ airfoil still has a larger lift to drag ratio at every α-value, as the parabolic curve has a greater amplitude than the baseline, Figure 10b [12].

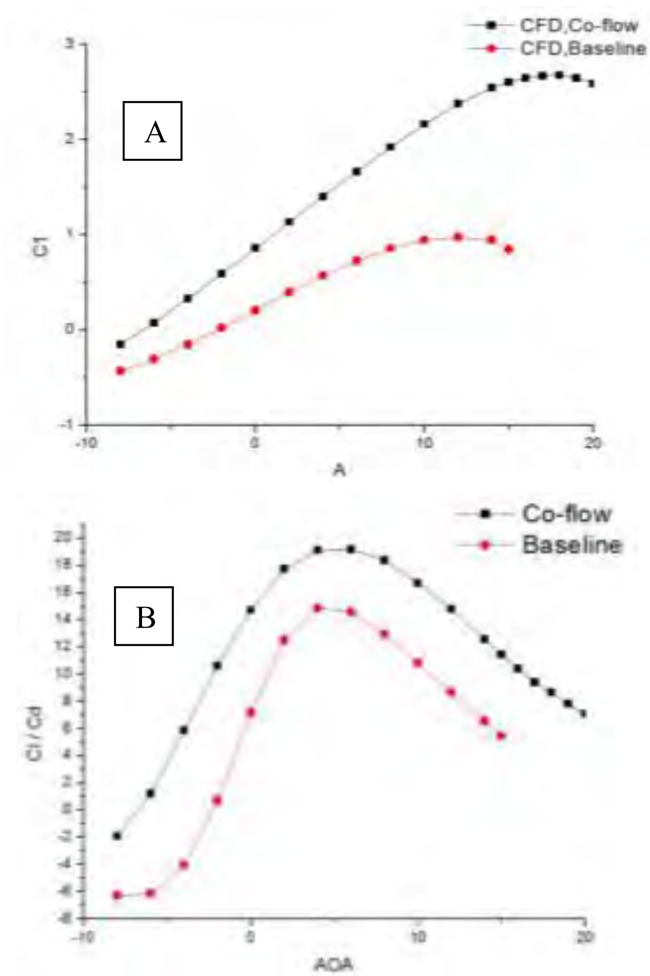

Figure 15: Top, lift coefficient vs angle of attack, bottom, the coefficient of lift versus drag as angle of attack increases. Black is the CFJ, red is the baseline airfoil [12].

So, the CFJ proves to have greater lift, negative skin-friction drag (x-pressure), and presence of typical induced drag (created by lift forces, and shown as y-pressure) when compared to the baseline airfoil. Research has also shown that the flow does not separate from the CFJ due to the jet flow until large α-values. As shown by Figure 11, the predicted model for a CFJ (bottom, Figure 11) is that flow separation does not occur like the baseline airfoil (top, Figure 11). This was tested through CFD at various angles of attack with fluid flow running over a CFJ airfoil. From this research, Figure 12, shows some of the α-values tested: i) 12°, ii) 20°, iii) 32°. This research found that flow separation begins at 26°, for this CFJ airfoil, so after this α-value the flow shows separation and turbulence, Figure 12iii. Further information on how various types of jet

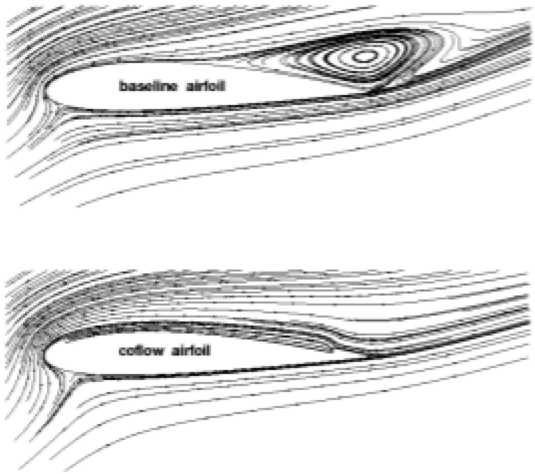

Figure 17: Flow field for the baseline NACA2415(bottom) and CFJ (top) airfoil at high angle of attack [13].

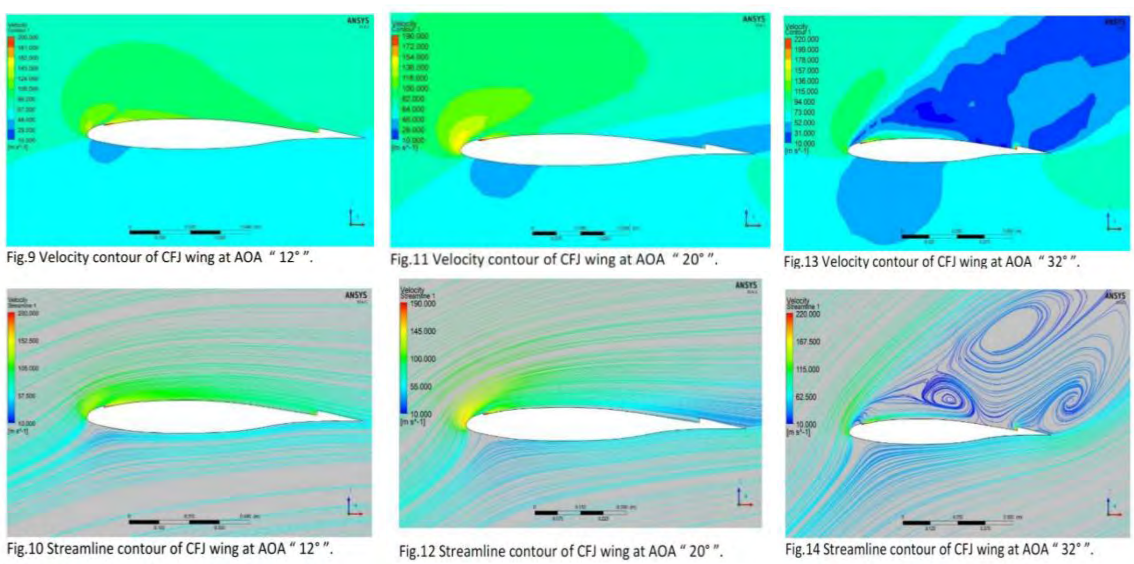

Figure 19: Various angles of attack for flow separation testing on CFD. i) 12°, ii) 20°, iii) 32°, with top pictures the velocity contour, bottom pictures streamline contours [13].

flow over a CFJ airfoils can be read in [14]. In addition, all pertinent numerical information from these research projects are summarized in Table 1. All of this will be further analyzed in the next section.

Table 1: Summary of pertinent information from various research papers. The baseline is the airfoil shape without CFJ components.

Reference #	Reynolds #	Mach #	Airfoil Shape	α	Cl max
[10]	$2x10^6$	0.1	NACA 6425	-5°-45° (stall)	~4.5
[11]	-	-	NACA 652-415	0°-10°	50x baseline
[12]	$3x10^6$	0.3	NACA 2415	-6°-19° (38% increase from baseline)	2.677 (88.52% higher than baseline max)
[13]	-	-	-	-4°-26° (lowest test, -4°)	52% form baseline

DISCUSSION

For advancement in flight and fuel consumption, the application of CFJ airfoils have potential as an alternative and produce a thrust force through negative drag that reduces fuel consumption. Research conducted, primarily at the University of Miami, has

shown in CFD and wind tunnel testing that these airfoils increase the stall margin by increasing the margin of usable angle of attacks. In addition, studies have shown an increase in lift coefficient values while reducing drag. These two trends are a trend shown in the summary of results, Table 1. These improvements are due to decrease in boundary layer separation, during turbulent air flow, mainly due to the addition of a jet stream over the airfoil arch increasing momentum while a force of negative drag is created. The focus of many CFJ airfoil papers, is that this negative drag force, or thrust, nullifies the need for typical combustion engines which would reduce carbon emissions and weight of airplanes in the future. However, these papers often overlook the need for some sort of initial energy or underplay the need for a vacuum source and fluid source. There needs to be some sort of energy input, for a plane to fly.

The jet stream for CFJ airfoils is created by an output slot near the leading edge and an intake slot towards the trailing edge where air is then recirculated. To do this a fluid source (like a pressurized air tank) or vacuum source (like an air pump) is needed. Zha and Dano, for US8485476 B2 patent are suggesting recirculation of air using a pump where mass flow is drawn in, at the recovery point, and, then, directed to a compressor that flows to the input slot, thereby saving energy expenditure through reuse [15]. This would be electrically powered with mechanical energy transfer from pumping air to high momentum jet stream which would be more efficient than the combustion process and eliminate emissions. The power needed for the pump depends on the total pressure change between input and recovery ports and the mass flow rate [16]. Nearly 80% of injection momentum is translated to drag reduction, and an engineless CFJ airplane could reduce power consumption by 70%. This is proved by the mass flow rate for the pump

varying from 9-17% of an engine's flow rate—meaning a CFJ pump requires less overall power than an aircraft with a combustion engine. The patent argues that compared to a typical combustion engine plane, a CFJ "engineless" plane conserves more mass flow, has a lower pressure change, no thermal energy loss, and less overall energy expenditure with less weight and drag from being engineless [15]. Following this logic of thinking the CFJ engineless airplane seems like the next solution in aircraft design. But looking at other patents and designs, there seems to be discrepancies with CFJ airfoils applications in engineless airplanes. In one patent, whose fee status was lapsed, the proposed aircraft design used the CFJ airfoil which included: an injection opening near the leading edge, a recovery opening located near the trailing edge, and one or more engine positioned after the recovery opening at the further portion of the trailing edge. So, a design that still uses engines. Although, these engines would be more integrated into the wing and use the intake slot to receives air for combustion, there was still use of an engine [16]. So, the question is how much thrust do CJF airfoils produce, and to what level and in what applications are they sufficient for aeronautical applications? Looking at Figure 9, there is a negative drag reported from Aguirre et. al. that shows a thrust force. However, since the y-axis is not labeled with a unit, it is hard to say if enough thrust is produced for typical airplane applications. And since the same research group has submitted another patent where CFJ aircraft sill requires engines, it seems like a far stretch to say that CFJ airfoils will lead to completely engineless planes. CFJ airfoils have been shown to increase lift for over a larger α ranges and reduce drag using a jet stream, but the design still requires an engine for typical thrust seen in commercial planes.

The CFJ airfoil does show promise with improving planes' lift versus drag, and increasing energy efficiency. This decrease in drag has a direct correlation to decrease in fuel, and this can be further improved by taking advantage of the CFJ design that would allow combustion engines to be more integrated into a plane's wing. The intake inlet, near the trailing edge of the airfoil, can be used for the air pump to recirculate air to the jet stream and to flow air to the engine for the combustion process. This allows for better engine integration, shown by Figure 13, so that the aircraft can be more aerodynamic creating less form drag. This is a simple process that improves engine integration while still producing thrust. So, some components of the CFJ do help reduce fuel consumption by providing a new air inlet for combustion engines.

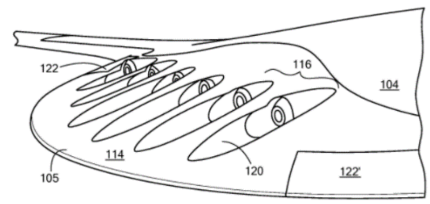

FIG. 23

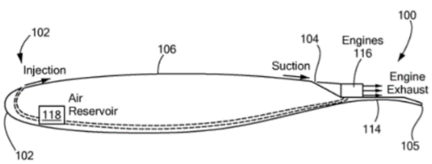

FIG. 24

Figure 21: Integration of engines into CFJ aircrafts, where oxygen intake is built into the air pump system for the jet stream [16].

Figure 22: Integration of engines into CFJ aircrafts, where oxygen intake is built into the air pump system for the jet stream [16].

The advantages that a CFJ design provides could be beneficial to some glider section of aircraft design. For example, the CFJ is like the bell-shaped span load seen on NASA's current Prandtl glider design, where specific twists in the wing produces thrust on the outer edges of a wing and produces an adverse yaw effects [17]. In particular, the CFJ could be good for the "[m]artian atmosphere due to reduced energy consumption, enhanced maneuverability and safety, extremely short take off/landing distance, soft landing and takeoff with very low stall velocity" which are needed in Mars alienated and

challenging conditions [16]. The high stall margins would help with flow separation in severe weather conditions and stall issues at low Re [15]. So, the CFJ airfoil could help NASA improve on their current design by expanding design to larger α, while increasing the lift to drag ratio but the design would still use the current propulsion method. These advantages could also be helpful in the Perlan glider project. Since the Perlan is towed up to mountain ranges where it uses the polar vortex winds to propel itself high up into the air, the CFJ airfoils could increase the lift to drag ratio of the current design. Since the glider already is designed to be engineless, the CJF design could help propel the Perlan to reach greater heights if the air pumps can be design to continue working at such high altitudes. The CFJ airfoil could have applications in gliders and integration of engines into a wing, and improves lift to drag ratios with less aptitude for stall.

CONCLUSION

In the 21st century aeronautical engineering could benefit from advancements in improving fuel efficiencies. With an increasing population, aircrafts' current 5% contribution to global warming will continue to increase [2]. The idea of 'engineless' aircrafts is appealing, but can it be realistic? There are current designs like the Prandtl and Perlan that take on glider designs, where the initial propulsion is done through other methods. But further research and work will be needed to make good progress in creating green aviation, and CFJ, co-flow-jet, airfoils are a start.

CFJ airfoils have shown increases in lift to drag ratios and increase in α margins so stall is less likely in harsher conditions. These CFJ airfoil have potential use in aeronautical vehicles for "unmanned reconnaissance aircraft, small personal aircraft,

commercial airliners, and many other applications" [16]. They have been promoted to help create engineless planes that rely on an electric air pumps, but research currently lacks proof of enough thrust, or negative drag, being produced for commercial applications. The CFJ components seem more likely to improve current designs with engines or for glider applications. In both applications, the aircraft will become more efficient. Application of CFJ airfoils with combustion engines will decrease drag under turbulent flow, by decreasing boundary layer separation, and allows for better integration of engines, since air intake for combustion would be provided from the jet stream's intake slot. So, drag and stall margin are reduced, while some thrust is also created thereby reducing fuel consumption. So CFJ airfoils better current aviation designs to be more sustainable and efficient, by adding a jet flow from an electric air pump and use of current propulsion methods.

REFERENCES

[1] “Airbus GMF 2016-2035 "Mapping Demand" (leaflet) ,” *Airbus GMF 2016-2035 "Mapping Demand" (leaflet)* . Airbus, 2016. <http://www.airbus.com/company/market/global-market-forecast-2016-2035/>

[2] E. Rosenthal, “Your Biggest Carbon Sin May Be Air Travel,” *The New York Times*, 26-Jan-2013. [Online]. Available: http://www.nytimes.com/2013/01/27/sunday-review/the-biggest-carbon-sin-air-travel.html. [Accessed: 25-Apr-2017].

[3] L. Cole, *Secret Wings of World War II: Nazi Technology and the Allied Arms Race*. South Yorkshire: Pen & Sword Aviation, 2015. ISBN 978 1 47382 344 0

[4] “Perlan, Reaching for High-Flung Pearls,” *Leonardo Times*, pp. 16–19, Jun. 2012.

[5] T. LeCompte, “Sailplane to the Stratosphere,” *Air & Space Magazine*, Jun-2016. [Online]. Available: http://www.airspacemag.com/flight-today/sailplane-stratosphere-180959154/. [Accessed: 25-Apr-2017].

[6] N. A. S. A., “Prandtl-D Aircraft,” *National Aeronautics and Space Administration*, pp. 1–2. <https://www.nasa.gov/sites/default/files/atoms/files/fs-106-afrc.pdf>

[7] Y. A. Çengel and J. M. Cimbala, *Fluid Mechanics: Fundamentals and Applications*, 3rd ed. New York, NY: McGraw-Hill Education, 2014.

[8] J. D. Anderson, “Ludwig Prandtl's Boundary Layer,” Dec-2005. PDF. <http://dept.math.lsa.umich.edu/~krasny/math654_prandtl.pdf> [Accessed: 06-May-2017].

[9] J. M. Meyers, D. G. Fletcher, and Y. Dubief, “MAE:123: Mechanical Engineering Laboratory II- Fluids Laboratory 7: Lift and Drag on an Airfoil,” *UVM*. PPT. < http://www.cems.uvm.edu/~jmmeyers/ME123/Lectures/ME%20123%20Lecture%209%20Airfoil%20(jmm).pdf> [Accessed: 06-May-2017].

[10] J. Aguirre, B.-Y. Wang, and G.-C. Zha, “Conceptual Design and Study of "Engineless" Airplane Using Co-Flow Jet Airfoil,” *25th AIAA Applied Aerodynamics Conference*, 2007. <http://www6.miami.edu/acfdlab/publications/AIAA-2007-4441.pdf>

[11] “Application of Co-Flow Jet Concept to Aircraft Lift Increase,” *International Journal of Advances in Mechanical & Automobile Engineering*, vol. 3, no. 1, Oct. 2016. <http://iieng.org/images/proceedings_pdf/IAE01162061.pdf>

[12] M. R. Nur, M. Assad-Uz-Zaman, and M. Mashud, “Effect of Co-flow Jet Over an Airfoil: Numerical Approach,” *Contemporary Engineering Sciences*, vol. 7, pp. 845–851, 2014.

[13] J. A. K. Sherief, A. Ajithkumar, G. K. P. Karlmarx, R. A. Jayandar, and S. Manikandan, "CO-FLOW JET CONTROL AS AN ALTERNATIVE FOR CIVIL AIRCRAFT HIGH LIFT CONFIGURATION," *AjithkumarCO-FLOW JET CONTROL AS AN ALTERNATIVE FOR CIVIL AIRCRAFT HIGH LIFT CONFIGURATION*, vol. 2, no. 4, pp. 1–5, Apr. 2014.

[14] B. Dano, G. Zha, and M. Castillo, "Experimental Study of Co-Flow Jet Airfoil Performance Enhancement Using Discreet Jets," *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, Apr. 2011.

[15] "Patent US8485476 - Discrete co-flow jet (DCFJ) airfoil," *Google Patents*. [Online]. Available: https://www.google.com/patents/US8485476. [Accessed: 06-May-2017].

[16] "Patent US8262031 - Co-flow jet aircraft," *Google Patents*. [Online]. Available: https://www.google.com/patents/US8262031. [Accessed: 06-May-2017].

[17] A. H. Bowers, O. J. Murillo, R. Jensen, B. Eslinger, and C. Gelzer, "On Wings of the Minimum Induced Drag: Spanload Implications for Aircraft and Birds," *NASA*, pp. 1–22, Mar. 2016.