Understanding boundary layer suction and its effect on wings
- A review

Ravindra S Kulkarni1, Benjamin Rohit2, Vignesh Lokanatha3, Chandrasekhar Lokesh3

1 Professor and Head, Department of Aerospace Engineering, RVCE, Bengaluru, Karnataka
2 Assistant Professor, Department of Aerospace Engineering, RVCE, Bengaluru, Karnataka
3 Department of Aerospace Engineering, RVCE, Bengaluru, Karnataka
E-mail: roemin25@gmail.com

Abstract. Boundary layer suction reduces drag by stabilizing the laminar boundary layer preventing transition and conceding higher regions of laminar flow. Boundary layer suction (BLS) also postpones boundary layer separation resulting in higher $C_{L_{\text{max}}}$, This phenomenon is particularly useful in the Aerospace sector and many applications are found and hence understanding the mechanics of BLS becomes critical. Consequently it becomes vital to understand the effect of BLS during different flight regimes and mission profiles. The objective of this review is to understand and document the understanding on BLS and its effects. The influence of location and position of suction, suction flow rate and suction hole width on aerodynamic performance by experiments and numerical analysis have been reviewed. It has been brought out that there is a convincing decrease in drag and pressure loss and an increase in max lift which in turn improves the overall performance of the aircraft. While multi-hole suction control can reduce drag much more efficiently than single hole suction control, position of the suction hole has a greater effect on reducing pressure losses than the suction flow rate. The factors affecting BLS and its effects on aerodynamic performance and overall performance of the aircraft has been discussed in this review.

Keywords: Laminar Flow Control, Boundary Layer Suction, Laminar - Turbulent Flow Transition

1. Introduction
Laminar flow control (LFC) has been known to have high potential to improve aircraft performance. The aircrafts fuel consumption and hence the range and endurance can be improved using LFC which is the
only known single aeronautical technology that offers such an improvement in performance. For transport airplanes the amount of fuel consumed could be reduced by 30% [1]. Laminar flow over most part of the wing due to low drag BLS can lead to improvement in L/D ratio and when L/D ratio is improved especially in long range aircrafts there is always a reduction in specific fuel consumption and in turn will increase the range of the aircraft at altitudes above 20,000 feet[2, 3]. LFC can be categorized into two, passive LFC and active LFC, passive LFC is beyond the scope of this paper. A combination of passive LFC which is known as the Natural Laminar Flow Control (NLFC) and active LFC is called Hybrid Laminar Flow Control (HLFC). Currently two principles of active LFC are under research which are surface cooling and boundary layer suction (BLS). It has been understood from previous research and literature that HLFC increases C_L, decreases C_D, reduces the boundary layer thickness and delays the transition of laminar to turbulent flow. BLS is an active type LFC where small amounts of energy input helps in keeping the boundary layer attached. Though BLS is extremely successful in delaying transition, increasing lift and decreasing drag, it has not been implemented on aircrafts due to its high maintenance in keeping the BLS holes clean. It is also true that once the flow is turbulent no combination of suction helps in reducing drag[4]. It was also observed that if BLS failed, then the max lift coefficient of the aerofoil drops below the max lift coefficient of the original airfoil without BLS[5].

BLS has also been very effective in reducing viscous drag. Two types of suction are generally used, discrete suction and distributed suction[6]. This paper surveys and reviews only BLS based LFC. LFC used in compressor blades would make it an exhaustive survey and hence has been neglected. BLS on compressor blades are out of the scope of this paper.

1.1. Historical Background
The very initial idea of suction being used as tool to control boundary layer dates back to the inception of boundary layer theory itself, Prandtl in his article The Mechanics of Viscous Fluids in Aerodynamic Theory, Vol. III in 1935 makes a mention of boundary layer control using suction[7]. Work on LFC began in the early 1930's with United Kingdom, Germany, and the United states using wind tunnels to test its effect. Initial tests using multiple suction slots resulted in laminar flow up to a Reynolds number of 7 million which was considered a phenomenon achievement during that period of time[1]. The very first flight experimentation began in the early part of 1940's where researchers placed suction holes between 20 and 60 percent of the chord on a B18 airplane. Research gained importance and peaked in the 1940's with the NACA 6 series airfoils. With the introduction of sweep in the 1950's due to high subsonic speed ranges the problem of cross flow came into effect. High subsonic and supersonic speeds require sweeping of wings and it was found that only suction can control the cross flow disturbances that helps in promoting boundary layer transition from laminar to turbulent flow [1] The work on suction based LFC further culminated in the 1960's with experimentation on aircrafts built by Britain and America. The application of suction based LFC had a new area of research in the 1970's which were related to supercritical wings. The present survey is to focus attention on the suction based LFC and to understand the mechanism of boundary layer suction. To gain a deeper insight into the developments of BLS during its early years of development the reader is referred to references [1] and [8].

1.2. Flight Tests
In the 1960's Northrop X-21 which was an experimental aircraft with 30° swept wings was equipped with BLS slots along the entire span of the wing under the supervision of Werner Pfenninger who was one of the pioneers in BLS. Experiments have been then performed on various aircrafts in the past which includes Dassault Aviation, Jetstar and Airbus to name a few, the results of these flight tests have been reviewed in this subsection.

Flight tests done on the German made aircraft DO-27 have shown that by using BLS the net drag during cruise can be reduced. The test results obtained on the DO-27 also accounted for the power requirement for the BLS [9]. The values of maximum lift by using BLS during flight test were similar to that of using leading edge slats. At higher angle of attacks where the flow over the fuselage had already
separated the aircraft was still maneuverable when BLS was switched on[9]. Flight tests early in 1941 were performed on a Douglas B-18 with BLS slots mounted on the left wing with the NACA 35-215 airfoil, the BLS slots were placed on the upper surface between 20 and 60 percent of the chord[10]. The Douglas B-18 was a twin engine mid wing monoplane with slot spacing of 5 percent of the chord.

2. Study on the Effect of Boundary Layer Suction on Performance

In this section, the effects of BLS on curved surfaces (airfoils) will be reviewed and not at plates. As the uid passes around the airfoil the ow is accelerated from the stagnation point onwards and at the trailing edge the ow is decelerated, if the ow is decelerated over a large part of the chord the adverse pressure gradient is not so severe enough to separate the boundary layer, by using BLS this limitation could be extended[11]. The total kinetic energy absorbed by the uid during acceleration is required to overcome the pressure gradient during deceleration in order for the uid to come to rest at the trailing edge after accelerating from the stagnation point[12]. But in the case of air which is a viscous uid the kinetic energy is lost due to friction, due to this loss the kinetic energy remaining is insu cient to overcome the pressure gradient and hence the ow does not come to rest at the trailing edge and there is present a velocity component in the direction of the motion of the wing.

Initial theoretical studies of BLS were developed for at plates where at very low Reynolds number no suction is required to keep the ow attached and stable, but in the case of airfoils the presence of adverse pressure gradient at the rear portion requires BLS at all Reynolds number to keep the ow laminar until the trailing edge[13]. Suction could be discrete or distributed over the chord and span of the airfoil and wing respectively to obtain best reduction in drag, increase in lift and delay in transition. Anderson et al.[14] studied suction distribution and de ned optimum suction distribution as the one in which minimum amount of suction is required at each suction point to delay/prevent transition.

Various factors a ects the e ciency of boundary layer suction. The suction pressure, suction hole position, the size of the suction hole, Reynolds number, boundary layer thickness are a few of the factors than can in uence the e ciency of the boundary layer suction in increasing lift reducing drag and delaying transition of laminar to turbulent ow. Reynolds number and suction rate in uence the boundary layer thickness which in turn could play a vital role in reducing drag[15].

2.1. Effect of Suction Coe cient and Pressure

It was found that by increasing the suction coe cient($C_q$) the $C_L$ increased and $C_D$ decreased, which also includes skin friction drag and pressure drag. But when $C_q$ reaches its critical value drag remains unchanged and also increases slowly[16]. It was also noted by Glauert et al.[17] that the airfoil with suction at low angle of attacks adhered to the quantity of suction required as per theoretical calculations but as the angle of attack increased and the ow separated the quantity of suction required to re-attach the ow was three to four times higher. Azim et al.[18] studied the e ect of suction pressure on trailing edge separation, it was found that the separation point moves towards the trailing edge with the decrease in the suction pressure. There is drastic improvement in the L/D ratio as the suction pressure is dropped. Kianoosh et al.[19] studied the e ect of suction coe cient on stall angle increase, and observed an increase in stall angle when there is an increase in the suction coe cient. The increase in suction coe cient also caused an decrease in the vortex formation behind the airfoil.

2.2. Effect of Suction Hole Width and Angle

Suction hole width also known and called as suction jet length has an e ect on the performance of BLS. Shi et al.[16] studied the impact of hole width during BLS and its in uence on performance and transition. It is a general understanding that suction hole width directly represents the suction mass, and hence by increasing the suction hole width it was noted that the boundary layer thickness grows thinner and, as a result of the decreasing boundary layer thickness $C_l$ is increased while skin friction drag initially decreased but later began to increase. As the boundary layer is thin and Reynolds number increases, there could be a possibility that the critical Reynolds number for roughness could exceed and induce large disturbances at the boundary layer[13]. On the contrary pressure drag had a continuous decreasing e ect with increase in suction hole width[16]. But a very large suction slot tends
to have a adverse effect on performance[11]. E. D. Poppleton[20] concluded based on his study of boundary layer suction on a 40 degree swept back wing that the size of the slot is function of choking conditions, the best slot size would be the one which is just not choking when $C_{\text{max}}$ is reached.

Kianoosh et al.[21] observed that when a suction perpendicular to the ow is used, not only does the L/D ratio improve but the stall angle also increases, in the case of a NACA 0012 airfoil the stall angle improved from 14° to 22°. The hole width also had a direct effect on the L/D ratio, where the increase in the hole width augmented the L/D ratio and delayed the separation further downstream[21]. It was also observed that the L/D ratio increased as the hole width increased to 2.5% of the chord and then insignificantly decreased. Kianoosh et al.[19] observed that when the suction jet length increased till 2.5% of the chord length the lift increased and drag decreased and as the suction jet length increased between 2.5% to 3% of the chord there was insignificant improvement.

BLS can be performed at various angle Huang et al.[22] studied the effect of varying suction angle and concluded that perpendicular suction (suction at 90 degrees to ow) has the largest impact to increase lift.

2.3. Impact of Suction Hole Position

2.3.1. Impact of Suction Hole Position on the Chord It is important to understand that there is a point on the airfoils chord which is the point of transition without any LFC. This point is called the natural transition point. Shi et al.[16] studied the effect of position of the BLS hole as a function of the chord length. It was noted that as the position of the hole moved towards the trailing edge $C_t$ increased and $C_{D}$ decreased. But a very important observation was made that after the BLS point moved past the natural transition point towards the trailing edge, the $C_t$ decreased and $C_{D}$ increased[16]. There is no possibility of a benefit of transition delay if the point is placed after the natural transition point as the transition from laminar to turbulent has already occurred and it has an adverse effect on aerodynamic properties[16]. Azim et al.[18] found that on the NACA 4412 airfoil the trailing edge separation began at 0.7c from the leading edge and a BLS slot when placed at 0.68c moved the trailing separation to 0.88c. When a slot is placed nearer to the leading edge at 0.56c and 0.48c the BLS decreased performance by decreasing lift and increased turbulence which causes an increase in drag 6 times to that of without suction. Azim et al.[18] concluded that placing the BLS slot only near to the separation point helps in reducing drag. Tutty et al.[23] also suggested that placing a BLS slot before the transition point makes BLS ineffective and placing the suction point after the transition point has no effect in delaying the transition. It has also been documented by iigt tests that leading edge suction helps in delaying transition and is a very effective means of increasing maximum lift, it has a similar effect to that of a leading edge slat[9, 22]. Kianoosh and Reza[24] observed that when the suction slot is placed near the leading edge at 10% of the chord there is a negligible effect below stall angle (14 degrees). But had a phenomenal impact on the L/D ratio beyond the stall angle. A. T. Piperas [25] observed that when the transition point is downstream the suction location a delay in transition can be achieved but when the transition point has moved upstream of the suction point, the suction becomes ineective. By placing the suction slot close to the leading edge one can improve the pressure difference between the upper and lower surfaces and the aerodynamic behavior[25]. Millard J Bamber[12] found that the best BLS slot location would depend on the angle of attack. After thorough wind tunnel test it was found that the best slot position for small angle of attacks is near the trailing edge and as the angle of attacks keeps increasing the BLS slot should move further upstream towards the leading edge[12]. Suction slot spacing when multiple slots are present is another area of concern, Dale et al.[26] concluded that when the slot spacing is very large the suction power required is very large and smaller suction slot spacing would cause a manufacturing challenge. It is a challenge to optimize the slot spacing when multiple BLS slots are used.

The position of suction hole is a problem without a conclusion as di erent authors conclude differently. There could be a possibility that di erent airfoils(t/c ratio), mach number, angle of attack, suction pressure, the application and the conditions at which boundary layer suction is used to improve performance could have di erent positions. Clearly there seems to be a need for further research in this area to sort out the discrepancies and to further understand the mechanisms of boundary layer suction and the positioning of BLS slots.
2.3.2. Impact of Suction Position on the Span of the Wing
Kianoosh and Reza[24] studied the effect of suction area on a 3-D wing by placing the suction area along the span of the wing. Two configurations were studied, tip suction and center suction where the width of the suction area was 2.5% of the chord. The location of the suction area was set to 10% of the chord from the leading edge.

When considering the overall effect, center suction was considered to be a better choice, where the L/D ratio increased better with center suction than tip suction[24]. When the length of the suction slot is greater than half the wing span center suction is better and when the suction length is less than half the wing span tip suction is better[24]. Leading edge contamination is often seen in a 3-D swept wing when the swept wing is attached to the fuselage or to the wall while performing a wind tunnel test. By placing the BLS slot near the leading edge of a swept wing along the attachment line it is possible to prevent the attachment line contamination[27].

H. J. B. van de Wal[28] as a part of his master thesis in Aerospace Engineering at TU Delft attempted to design a wing with boundary layer suction by redesigning the wing of the Euro-ENAER EE10 Eaglet, a research aircraft of TU Delft. The most critical region where most suction was needed was at the wing tip and the least needed was at the root. Also when aps were deployed the suction required was less. H. J. B. van de Wal[28] also concluded that there was no need of suction at the wing root due to the roughness which would trigger a turbulent boundary layer immediately and another reason for turbulent ow in that region is due to wake generated from the propellers. The flight parameters also had an improvement due to the Eaglets new wing with BLS installed. The total drag reduction was very small as the wing profile drag is a relatively small portion of the aircrafts total drag. The aircraft had a steeper lift curve when compared to the original[28].

2.4. Effect of Suction Amplitude and Suction Velocity
When a 2-D airfoil with BLS is investigated there is no cross-ow (CF) effect, ows with the absence of CF leads to different ow physics. 3-D wings especially swept wings have the effect of cross-ow which should be considered while analyzing boundary layer suction on wings[29]. Kianoosh et al.[19] defined suction amplitude as the ratio of suction velocity to free stream velocity. Three suction amplitudes were considered, 0.1, 0.3 and 0.5 and the increase of suction amplitude from 0.3 to 0.5 had a greater effect in increasing lift and reducing drag and hence an improvement in the L/D ratio. The maximum L/D ratio was obtained at a suction amplitude of 0.5[19]. Below a suction amplitude of 0.01 there seemed to be no significant effect due to BLS, but above the suction amplitude of 0.01 lift increased as suction amplitude increased[22]. It was noted by Robert et al.[30] that below the critical value of suction velocity which is the minimum suction velocity the drag increased with a decrease in the suction velocity and above the critical suction velocity the drag remained constant[30].

2.5. Effect of Slats and Flaps
The effect of high lift devices on BLS have been rarely studied, a few researchers attempted to understand the influence of high lift devices on BLS and this has been reviewed in this subsection. The deflection of aps also tends to influence the efficiency of BLS. It has been found experimentally that there is an increase in Cmax from 1.9 to 2.2 when BLS was applied for a 0.2 chord split ap which was detected by 60°. But higher suction pressure may be required to be able to balance the addition pressure difference caused due to the deflection of the aps[31]. Extension of leading edge slats tend to delay leading edge separation and it was found that a suction slot closer to the leading edge has a more favorable influence on the maximum lift of the airfoil without slat[32].

3. Effect of Boundary Layer Suction on Aerodynamic Parameters
Boundary layer suction as we know improves aerodynamic parameters like increase in Cl, decrease in Cd, delaying stall and delaying the onset of turbulent boundary. A few of these parameters have been reviewed in the previous sections. In this section the effect of BLS on a few other aerodynamic parameters will be reviewed.
Stall delay is one of the advantages of BLS and stall in a plain wing without suction appears to be because of leading edge stall but whereas the stall in a wing with BLS present is a result of boundary layer separation at the trailing edge[30]. Also the stagnation point moves forward further for a wing with BLS in comparison to a plain wing as the angle of attack is increased. With the introduction of BLS airfoils with higher thickness to chord ratios(t/c) can be used without the high drag expectation due to separation[11]. Though it has been found experimentally that no significant decrease in drag is possible for airfoils with normal thickness on which separation does not occur[33].

Another possible feature of BLS is that it could improve the lateral control of the aircraft. As lift could be increased with BLS, a rolling moment could be produced by varying the wing pressure in the outermost region of the wing[12].

4. Mathematical Models Used in Numerical Analysis to Predict the Effects of Boundary Layer Suction

Flow over an 2-D airfoil can exhibit di erent complex phenomena such as wakes, ow separation, boundary layers etc. Computational Fluid Dynamics(CFD) developing at such a rapid pace is being used to predict not the 2-D airfoil but also the nite wing which is a 3-D body. The 3-D eects such as downwash, induced drag, trailing edge vortex can also be predicted using CFD. Experimental work is very important to produce data that is required to analyze suction based ow control. Obtaining very ne and sensitive detailing requires repetitive experimentation which could be an expensive a ir. Hence numerical methods/analysis could be used to capture and predict the eects. Various techniques and mathematical models are available to capture the physics. Di erent transition and turbulence models used to predict the transition from laminar to turbulent ow have been reviewed in this section.

RANS(Reynolds-averaged NavierStokes) is an cost e ective method compares to DNS(Direct Numerical Simulation) or LES(Large Eddy Simulation)[34]. Shi et al.[16] took a numerical approach to analyze hybrid laminar ow control (HFLC) using the Menter and Langtry's transition model. Computational results which were obtained were validated using experimental results. It was found that the Menter and Langtry's transition can predict the transition of boundary layer from laminar to transition when boundary layer suction was present. Sun et al.[35] studied boundary layer suction on a linear compressor cascade using RMS (Reynolds Stress Model) which was described in literature as the most suitable for complex three-dimensional separations. Azim et al.[18] investigated the e ect of BLS using the Spalart Allmaras turbulence model. The Spalart Allmaras turbulence model is a single equation linear eddy viscosity model which was initially designed for aerodynamic ows. Kianoosh and Reza[24] studied the e ect of 3-D suction on a NACA 0012 wing using RANS with the K- SST turbulence model which can predict ows with separation very accurately[24]. Kianoosh et al.[21] used RANS equations in conjunction with the Menter's shear stress turbulent model which is two equation model(K- SST) which is as mentioned capable of predicting ows with separation. A. T. Piperas [25] concluded that the SST Gamma Theta turbulence model predicts the eects of transition better than the K- SST model.

Dierent turbulent and transition models were studied to verify the equations ability to predict turbulence and transition by Serdar et al.[34] and it was found that the K-! SST transition and turbulent model tends to under-predict turbulence and the K- RNG over-predicted the stall. The K K! model was found to be relatively better in agreement with available experimental data.

5. Summary

There is a signi cant improvement in aerodynamic performance due to laminar ow control by BLS and hence an improvement in the overall performance of an aircraft with active BLS. With the increase in suction coe cient lift and stall angle increased with the decrease in the drag and vortex formation behind the airfoil. A conclusion on the most e ective BLS slot position could not be drawn, further research into optimization of slot position is a requirement. There was a decrease in the boundary layer thickness and pressure drag reduction with the increase in suction hole width. When suction is applied at center of the wing span it improves the L/D ratio better than when the suction is applied at the tip of the wing span. BLS near the leading edge if the wing can prevent attachment line contamination.
Higher suction amplitude influences improvement in lift and reduction in drag. Higher t/c ratio airfoils can be used when BLS is used without the increase in drag due to boundary layer separation. There is also a possibility of better lateral control of an aircraft when BLS is present and active. The $K_K$ model was considered to be the best turbulence model to predict the effect of BLS and flow separation while using computational fluid dynamics to analyze BLS.

References
1. Albert L. Braslow. A history of suction-type laminar-flow control with emphasis on flight research. Monographs in Aerospace History, 13, 1999.
2. W. Pfenninger and John W. Bacon. Design studies of Long Range Laminar Suction Airplanes at High Subsonic Speeds. Summary of Laminar Boundary Layer Control Research, WADC Tech. Rep. 56-111:294, 1957.
3. W. Pfenninger. Note about the range performance of high altitude long range photoreconnaissance airplanes With low drag boundary layer suction. Summary of Laminar Boundary Layer Control Research, WADC Tech. Rep. 56-111:329, 1957.
4. Smith A. M. O and Clutter D. W. Studies and experiments in drag reduction by boundary layer control. Douglas Aircraft Co, 1956.
5. E. J. Richards, W. S. Walker, and C. R. Taylor. Wind-tunnel Tests on a 30 per cent. Suction Wing. Aeronautical Research Council Reports and Media, Reports and Memoranda No. 2149, 1945.
6. Richard Eppler. Airfoils with boundary layer suction, design and o -design cases. Aerosp. Sci. Technol., 3, 3, 1999.
7. J. H. Preston. The Boundary-layer Flow over a Permeable Surface through which Suction is Applied. Aeronautical Research Council Reports and Media, Reports and Memoranda No. 2244, 1946.
8. Dennis M. Bushnell and Marie H. Turtle. Survey and Bibliography on Attainment of Laminar Flow Control in Air Using Pressure Gradient and Suction. NASA Reference Publication 1035, 1, 1979;
9. F. Schwarz and W. Wuest. Flight tests and wind tunnel measurements on airfoils with boundary layer suction for increasing maximum lift. Aerodynamische Versuchsanstalt Gottingen.
10. John A. Zalovcik, J. W. Wetmore, and Albert E. von Doenhoff. Flight investigation of boundary layer control by suction slots on an NACA 35-215 low drag airfoil at high Reynolds number. NACA, Report 4B29, 1944.
11. S.P. Dirlik, K.R.Kimmel, A.Sekelsky, and J.F. Slomski. Experimental evaluation of a 50 percent thick airfoil with blowing and suction boundary layer control. AIAA, 1992.
12. Millard J Bamber. Wind tunnel tests on airfoil boundary layer control using a backward opening slot. NACA, Report 385, 1932.
13. Albert L B, Dale L B, Neal T, and Fioravante V. Experimental and theoretical studies of area suction for the control of the laminar boundary layer on an NACA 64A010 airfoil. Langley Aeronautical Laboratory, Report 1025, 1951.
14. G F Anderson, V S Murthy, and S P Sutera. Laminar Boundary-Layer Control by Combined Blowing and Suction in the Presence of Surface Roughness. J. Hydronautics, 3(3):145 151, 1969.
15. O. Oyewola, L. Djenidi, and R. A. Antonia. Combined in uence of the Reynolds number and localised wall suction on a turbulent boundary layer. Experiments in Fluids, 35:199 206, 2003.
16. Shi Yayun, Bai Junqiang, Hua Jun, and Yang Tihao. Numerical analysis and optimization of boundary layer suction on airfoils. Chinese Journal of Aeronautics, 28(2):357 367, 2015.
17. M. B. Glauert, W. S. Walker, W. G. Raymer, and n. Gregory. Wind-Tunnel Tests on a Thick Suction Aerofoil with a Single Slot. Aeronautical Research Council Reports and Media, Reports and Memoranda No. 2646, 1948.
18. R. Azim, M. M. Hasan, and Mohammad Ali. Numerical investigation on the delay of boundary layer separation by suction for NACA 4412. Procedia Engineering, 105:329 334, 2015.
[19] Kianoosh Youse, S. Reza Saleh, and Peyman Zahedi. Numerical Investigation of Suction and Length of Suction Jet on Aerodynamic Characteristics of the NACA 0012 Airfoil. International Journal of Materials, Mechanics and Manufacturing, 1(2), 2013.

[20] E. D. Poppleton. Boundary-layer Control for High Lift by Suction at the Leading-edge of a 40 deg Swept-back Wing. Aeronautical Research Council Reports and Media, Reports and Memoranda No. 2897, 1951.

[21] Kianoosh Youse, Reza Saleh, and Peyman Zahedi. Numerical study of blowing and suction slot geometry optimization on NACA 0012 airfoil. Journal of Mechanical Science and Technology, 28(4):1297–1310, 2014.

[22] L. Huang, P. G. Huang, and R. P. LeBeau. Numerical Study of Blowing and Suction Control Mechanism on NACA0012 Airfoil. Journal of Aircraft, 41(5), 2004.

[23] O. R. Tutty, P. Hackenberg, and P. A. Nelson. Numerical Optimization of the Suction Distribution for Laminar Flow Control. AIAA Journal, 38(20):370–372, 1999.

[24] Kianoosh Youse and Reza Saleh. Three-dimensional suction flow control and suction jet length optimization of NACA 0012 wing. Meccanica, 50:1481–1494, 2015.

[25] Apostolos Tentolouris Piperas. Investigation of Boundary Layer Suction on a Wind Turbine Airfoil using CFD. DTU Mechanical Engineering, 2010.

[26] Dale L. Burrows and Milton A. Schwartzberg. Experimental investigation of an NACA 64A010 airfoil section with 41 slots on each surface for control of laminar boundary layer. NACA, Technical Note 2644, 1952.

[27] J.C. Juillen and D. Arnal. Experimental Study of Boundary Layer Suction Effects on Leading Edge Contamination along the Attachment Line of a Swept Wing. Laminar-Turbulent Transition, 1995.

[28] H.J.B. van de Wal. Design of a Wing with Boundary Layer Suction. Faculty of Aerospace Engineering, TU Delft, 2010.

[29] Ralf Messing and Markus J Kloker. Investigation of suction for laminar flow control of three-dimensional boundary layers. J. Fluid Mech., 2010.

[30] Robert E Dannenberg and James A Weiberg. Section Characteristics of a 10.5 Percent thick airfoil with area suction as affected by chordwise distribution of Permeability. Ames Aeronautical Laboratory, NACA Technical Note 2847, 1952.

[31] James A. Weiberg and Robert E . Dannenberg. Section characteristics of an NACA 0006 airfoil with area suction near the leading edge. Ames Aeronautical Laboratory, 1954.

[32] John H. Quinn Jr. Tests on a NACA 641A212 airfoil with suction with a slab, a double slotted and boundary layer control by suction. NACA, Technical Note 1293, 1947.

[33] E. J. Richards and C. H. Burge. An Aerofoil Designed to give Laminar Flow over the Whole Surface with Boundary-Layer Suction. Aeronautical Research Council Reports and Media, Reports and Memoranda No. 2263, 1943.

[34] M. Serdar Genc, Unver Kaynak, and Huseyin Yapici. Performance of transition model for predicting low Re aerofoil flows without/with single and simultaneous blowing and suction. European Journal of Mechanics B/Fluids, 30:218–235, 2011.

[35] Sun Jinjing, Liu Yangwei, Lu Lipeng, and Wang Qiuhui. Control of Corner Separation to Enhance Stability in a Linear Compressor Cascade by Boundary Layer Suction. Procedia Engineering, 80:380–391, 2014.