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Experimental Study on the Effect of Boundary Layer Control on the Aerodynamics Characteristics of NACA 0021 Aerofoil

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ABSTRACT

Take-off and landing are the critical phases of an aircraft flight where there is a high demand of lift force at the lowest stalling speed of aircraft. Use of different techniques to increase the lift force during these phases of flight is one of the prime objectives in the design of an aircraft wing. Delaying and eliminating flow separation using boundary layer control (BLC) techniques will improve the aerodynamic characteristics of a wing. This work presents an experimental study on the effect of BLC on the aerodynamic characteristics of NACA 0021 aerofoil. Both the techniques of blowing and suction has been considered in this study. Model was built using composites and tested in a subsonic wind tunnel integrated with a compressor/vacuum pump setting for to control the boundary layer on the aerofoil. Firstly, the model with 20 pressure tappings was tested without BLC and the point of flow separation was noted. Later, the suction and blowing holes were made suitably in the model and equipped with a compressor/vacuum pump to control the boundary layer and study the effects of it on the performance of NACA 0021 aerofoil. As expected, the BLC by both the techniques show improvement in the maximum lift coefficient.

1. Introduction

The investigation of boundary layer control on an aerofoil has been ongoing since mid-20th century. The presence of the boundary layer has produced many design problems in all areas of aerodynamics. However, the most intensive investigations have been directed towards its effect upon the lift and drag of wing. Today, the application of this boundary layer control can be seen in every aircraft, including the military aircraft and civil transportation aircraft. The techniques have been developed to manipulate the boundary layer, either to increase the lift or decrease the drag. The better the manipulation, the better performance the aircraft would achieve.

Aircrafts are designed for the best aerodynamic efficiency which is attained by choosing aerofoils that results in least drag. The predominant drag component in an aircraft is the skin friction drag component which is directly related to the high shear stresses that results from turbulent boundary layers and its separation. This problem of turbulent boundary layer separation has been the subject

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of interest in the literature for the past few decades. An earlier review work on this subject by Gad-el-Hak and Bushnell [1] and recently by Abbas *et al.,* [2] reveals that numerous works has been carried out in this field. Abbas *et al.,* [2] reviewed the present the state of the art of different technologies oriented to the active and passive control for turbulent skin-friction drag reduction. With the complexity involved in the phenomenon of boundary layer separation such as large-scale unsteadiness and 3-D effects the interest in the study has extended even until recently. Viswanath *et al.,* [3] experimentally investigated the effectiveness of tangential blowing inside the separation bubble to control an axisymmetric separated flow at low speeds.

BLC is still an attractive field, with the development of modern technologies the BLC was achieved through new techniques such as using electric fields and plasma actuators with spanwise travelling waves [4-6]. Separation control by both passive and active means is widely employed for improving aerodynamic performance. Qiao *et al.,* [7] experimentally studied the control of a turbulent boundary layer over a flat plate based on wall perturbation generated by piezo-ceramic actuators. Kurz *et al.,* [8] used active control approach on the BLC on heavily loaded turbine blades. Salam *et al.,* [9] studied experimentally and numerically BLC analysis and the influence of the Magnus effect on an aerofoil with a leading-edge rotating cylinder. Silva and Malatesta [10] carried out numerical simulation of the BLC on the NACA 0015 aerofoil through vortex generators whereas Li *et al.,* [11] used numerical computational fluid dynamics to study the effect of BLC on the airfoil noise reduction. Recently Ramsay *et al.,* [12,13] studied the effect of the suction BLC on the elimination of boundary layer separation on cylinders and axisymmetric diverging channel. Very recently Liang *et al.,* [14] studied numerically the effect of an injection of flow of an NACA 0012 aerofoil to control the boundary layer separation effectively.

Based on the above literature review, we can note that BLC is still an active field of research and still more to explore in this field. In this work, an aerofoil model of NACA 0021 has been fabricated and the pressure distribution along the aerofoil surface was obtained to determine the exact location of boundary layer separation from the surface. Based on the separation points the holes were made on the aerofoil for BLC by the method of suction and blowing. Then BLC is applied on the aerofoil and through experimental investigation, the coefficient of pressure, Cp, was obtained to calculate the maximum lift coefficient. Thus, the aim of the work is to develop an aerofoil model equipped with boundary layer control setup and to study experimentally the most important characteristics of the aerofoil such as the point of flow separation and the effect of BLC on the C_{lmax} of the aerofoil.

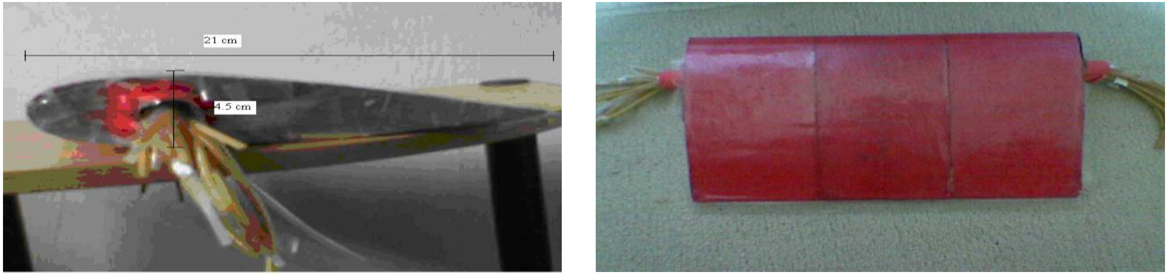
2. Methodology

2.1 Model Fabrication

As a first step, to study the effects of the BLC, an aerofoil was chosen carefully from the NACA family of aerofoils. Aerofoil that can be fabricated easily and with maximum thickness need to be chosen so that the thickness is large enough to accommodate the 20 tubes for pressure tappings and blow/suction pipes that need to be inserted in the aerofoil. NACA 0021 was a suitable choice with symmetric profile and with high thickness and thus the profile data of this aerofoil was downloaded from the Profili aerofoil database [15]. Based on this profile the model was fabricated with the length of the chord of 21 cm and with a maximum thickness of 4.5 cm as shown in Figure 1(c).

The printed dimension of the aerofoil was drawn on the foam and then, using hot wire equipment, the foam was cut according to the dimension (Figure 1(a)). To make the foam model strong and stiff to withstand the aerodynamic forces, five layers of fiber glass were reinforced on the foam. Then the internal foam was carefully removed (Figure 1(b)) so that aerofoil was made hollow to make room for tubes from tappings and BLC setup tubes (Figure 1(d)).

(a) Aerofoil model was cut into half (b) Hollow aerofoil model



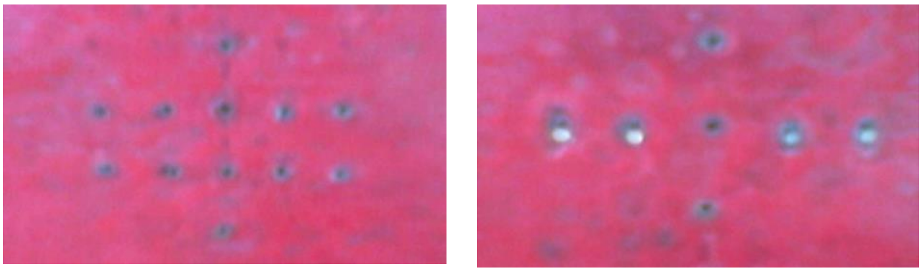
(c) Dimension of NACA 0021 aerofoil (d) NACA 0021 model ready for testing

Fig. 1. Fabrication of NACA 0021 model

The finished composite hollow aerofoil model was drilled with a total of 20 holes, with 15 holes along upper surface with the spacing of x/c = 0.05 between them and 5 holes on the lower surface with the spacing of x/c = 0.15 between them from leading edge to trailing edge in one line for pressure tappings. Needles were inserted into the holes and by using epoxy resin those needles been glued from inside the aerofoil. Further step was to attach all needles with tubes and pull it out of the aerofoil. Finally, these tubes were labeled with numbering to show the position for each needle. The aerofoil surface needs to be as smooth as possible to make sure that when it is being tested, the flow would be laminar, thus the projecting needles were trimmed and filed carefully on the upper and lower surface of aerofoil ensuring that the holes are not closed. The surface was smoothed by using soft sandpaper and then painted to make the surface clean from dust or dirt. Finally, the symmetric aerofoil was covered up with a layer of plastic sheet.

2.2 Method of Suction and Blowing

For suction and blowing methods, a standard vacuum pump and a blowing pump [BB 8000 Air Pump] was integrated in the setup as shown in Figure 3, the pipes from this equipment were connected to the corresponding suction/blowing holes made in the aerofoil (Figure 2(a) and Figure 2(b)). The vacuum pump would inhale the air from the aerofoil surface whereas the blowing (aquarium) pump would exhale the air on the upper surface of aerofoil. The combination would produce greater effect in terms of improving the lift performance of the aerofoil.



(a) (b)

Fig. 2. (a) Suction Holes on the Aerofoil (near orifice 12 and 13) and (b) Blowing Holes on the Aerofoil (near orifice 7 and 13)

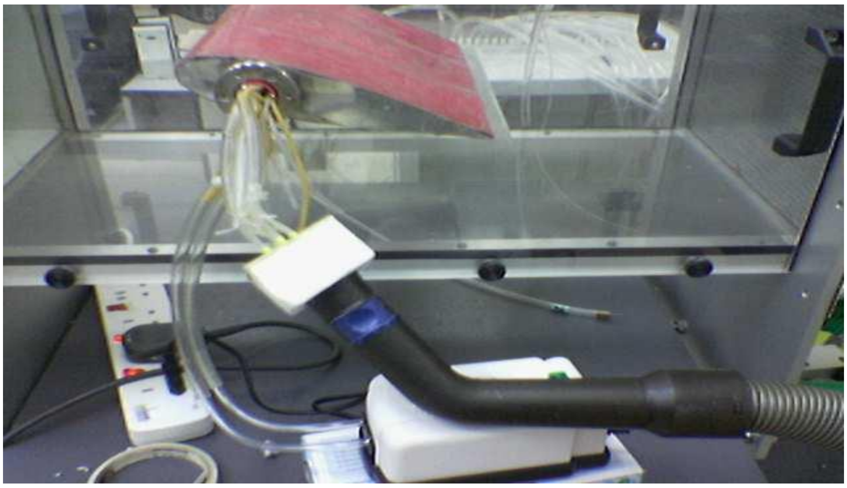


Fig. 3. Combined setup of suction and blowing

2.3 Experimental Procedure

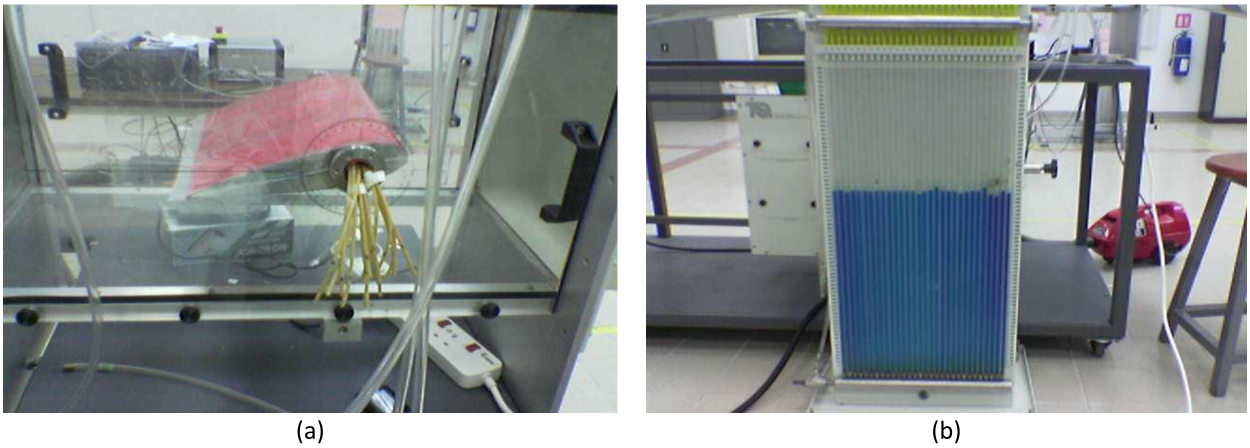
The aim of experiment is to measure the pressure distribution without and with applying the boundary layer control setup; suction and blowing around the NACA 0021 at various angles of attack. The apparatus used were Subsonic Wind Tunnel TE54, Pitot – tube, manometer, aerofoil NACA 0021 and computer. The subsonic wind tunnel TE54 used is as shown in Figure 4 at International Islamic University Malaysia is with closed working section and it is of open return suction type. The test section is of a square section with acrylic roof and floor as shown if Figure 4.

Fig. 4. TE54 Subsonic Wind Tunnel

Firstly, the aerofoil was installed (Figure 5(a)) in the wind tunnel test section and the tubes were connected to a set of manometers (Figure 5(b)). Then, the angle of attack is being set starting from 0°, 4°, 8°, 10°, 11°, 12°, 13°, 14° and finally at 15°. Next, the reference velocity upstream of the aerofoil was measured. All pressures were recorded, and the ambient temperature was recorded. These procedures were repeated with the boundary layer control setup. The sequences of pressure measurement along the aerofoil upper and lower surfaces were as follows:

i. Pressure measurements without applying the boundary layer control setup.
ii. Pressure measurements with the aid of blowing.
iii. Pressure measurements with the aid of suction.
iv. Pressure measurements with the aid of suction and blowing.

The results from experiment were tabulated and presented in the form of graphs of pressure coefficient, Cp vs x/c and then the C_L vs α curves are plotted based on this graph.



(a) (b)

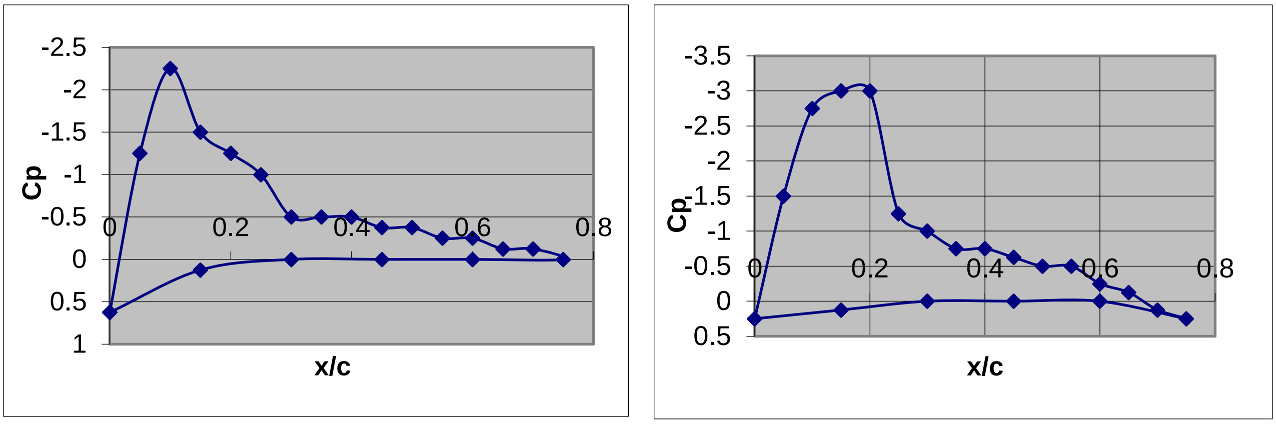
Fig. 5. (a) NACA 0021 model inside the test section and (b) manometer

3. Results and Discussion

3.1 NACA 0021 Aerofoil without Boundary Layer Control

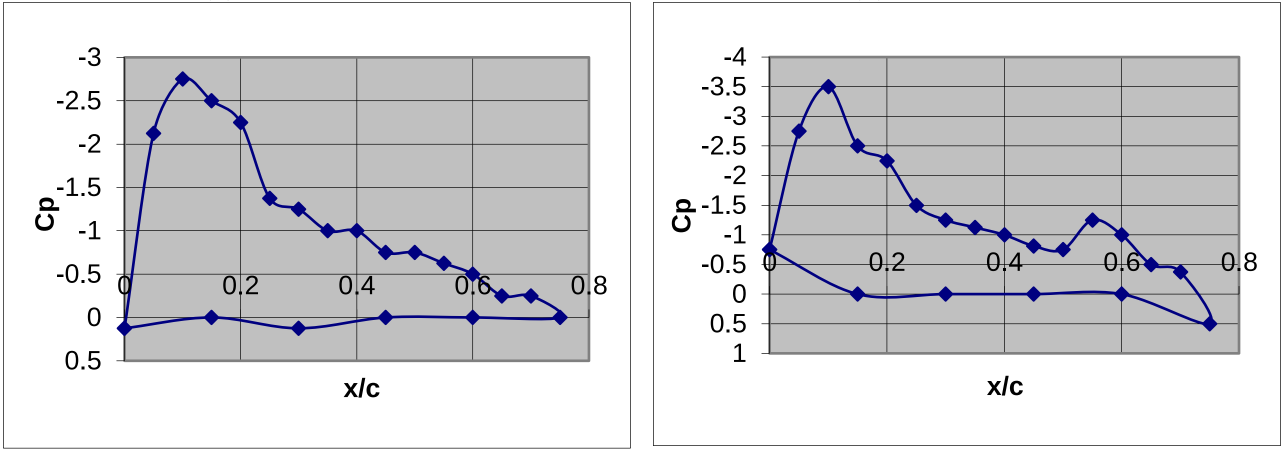
Before studying the effect of BLC, the NACA 0021 aerofoil was tested in the wind tunnel to understand its basic aerodynamic characteristics. Thus, the NACA 0021 model alone with 20 pressure tappings on it was mounted on the wind tunnel and the experiment was conducted for different angle of attack. The results obtained from the manometer readings were converted to Cp and the following plots of Cp vs x/c (Figure 6) were made [16].

Based on the obtained results for Cp vs x/c (Figure 6), it can be noted that between 0° to 10° angles of attack (typical results for 4°, 8°, 10°, and 12° are shown in Figure 6(a) to Figure 6(d) respectively), for low angle of attack, the adverse pressure gradient is moderate; that is *dp/dx* is small. The flow remained attached to the aerofoil surface except for a small region near the trailing edge. However, when the angle of attack is increased to 12° and above, as shown in Figure 6(d), the pressure coefficient showed a sudden change at point 12 (x/c =0.55). At this point, the pressure gradient, *dp/dx* would be large. In this case, the real viscous flow tends to separate from the surface thus leading to boundary layer separation. Since the exact location of separation has been detected, a boundary layer control (suction) can be applied near to this point or specifically at 'point 12' (x/c=0.55) for to delay the separation.



(a) Aerofoil at α = 4°

(b) Aerofoil at α = 8°



(c) Aerofoil at α = 10°

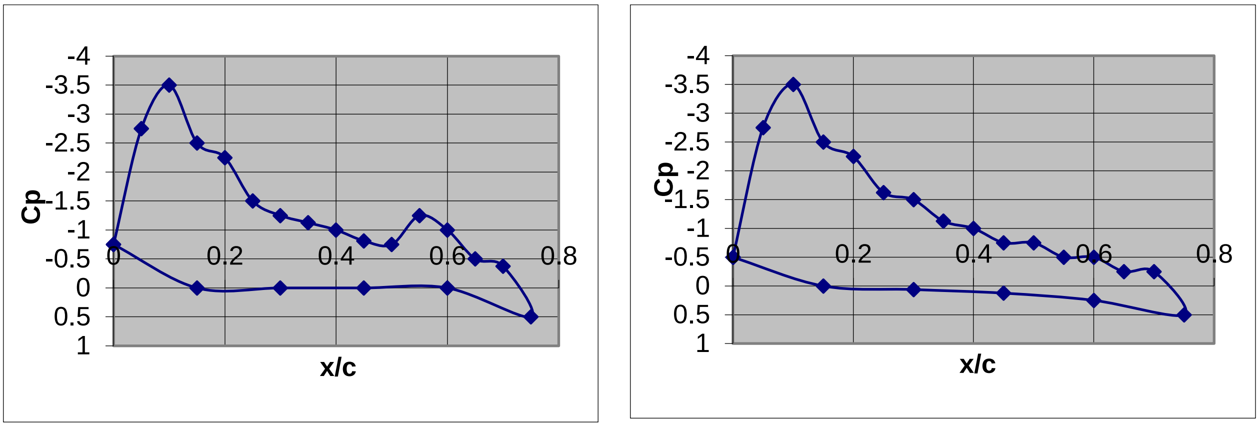
(d) Aerofoil at α = 12°

Fig. 6. Pressure distribution on the NACA 0021 aerofoil for different angle of attack

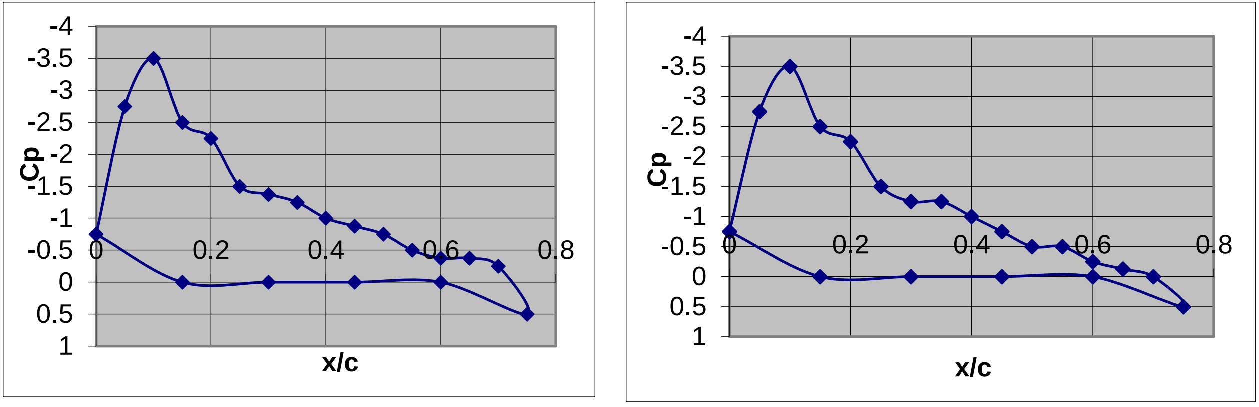
3.2 Pressure Distribution for NACA 0021 Aerofoil with BLC

With the point of separation known from the initial study, as a next step the effect of BLC is studied. First the effect of suction is considered, then the effect of blowing and finally the combined effect of both suction and blowing is studied.

While in first part, the exact location of flow separation of NACA 0021 has been determined (at point 12, at x/c=0.55 as shown in Figure 7(a)). Hence, the suction is applied at point 12 and 13 i.e., at (x/c) = 0.55 and 0.6 respectively using the vacuum pump as shown in the setup in Figure 2(a). The effect of suction can be readily seen through the results obtained (Cp vs. x/c) in Figure 7(b). From the observation, the applied suction has increased the pressure coefficient (Cp) on both specific points. The layer of lower-energy (“tired”) air near the surface approaching this separation point is removed through a suction slot. As a result, a much thinner, more vigorous, boundary layer is produced that is able to progress further along the surface against the adverse pressure gradient without separation. However, the separation tends to occur again at α = 14° (starting at orifice 8, or x/c=0.35) as the angle of attack is being increased again. The maximum lift coefficient recorded is 1.2 as compared to the case without BLC, which was 1.125, proving that the suction method improves the lift performance.



(a) Aerofoil without BLC (b) Aerofoil with suction



(c) Aerofoil with blowing (d) Aerofoil with blowing and suction

Fig. 7. Pressure distribution on the NACA 0021 aerofoil at α = 12° with BLC

Next for the case of blowing, the results are presented in Figure 7(c) which shows the effect of blowing method on the pressure distribution on the aerofoil. As the exact location of flow separation has been determined (at point 12 at α = 12°), so well ahead the blowing holes are placed near tapping hole 7 so that the tired air which is about to separate is re-energized by blowing air through the air pump (Figure 3). Hence, the blowing is applied at point 7 and 13 as shown in Figure 2(b) (x/c = 0.3

and 0.6 respectively). The stalling angle of attack is increased and higher than the aerofoil without blowing. Again, the maximum lift coefficient is recorded at 1.2 compared to the case without BLC which was 1.125, proving that the blowing method also improves the lift performance and delayed the stall.

Finally, both the methods of BLC (suction and blowing) have been applied simultaneously to study the combined effect on the lift characteristics of the NACA 0021 aerofoil. The effects of both methods on the air flow along the aerofoil surface could be seen from the Figure 7(d). As for the Cp distribution along the aerofoil chordwise, the outcome showed increment in the value of Cp especially at the critical point of separation. When the energy of the airflow tends to decrease, this low energy flow is sucked through the suction and as the airflow is moving further towards trailing edge, the blowing mechanism supplied energy to the airflow to energize back the tired air near the surface. As a result, the separation point had been delayed further. Hence, both methods have efficiently increased the lift coefficient to 1.33 and delayed the flow separation to certain angle of attack (α = 14°).

From the inspection of the complete experimental results from Figure 7, the outcomes had proved the effectiveness of the boundary layer control setup by method of suction and blowing. The Figure 7(a) Figure 7(d) showed the comparison between all 4 different cases, the C_p distribution along the aerofoil surface. From the observation, both methods had effectively increased the lift performance of the aerofoil either by increasing the lift stall coefficient or by moving up the stall angle of attack. For example, the maximum value for C_l had increased from 1.125 to 1.2 when the control by suction and blowing applied separately. Thus, the lift performance has increased by 6.67% in both the cases. Finally, the combination of suction and blowing methods have produced a significant effect on both the $C_{l\ max}$ and the stall angle of attack. The $C_{l\ max}$ value had been raised to 1.33 (18.22% improvement) and the stall angle has been increased to 14°. Overall, the applied BLC setup enhanced the lift performance of NACA 0021. As obviously seen from the graphs, the flow patterns showing that the results achieved are acceptable and correlated to the theory.

The below Table 1 summarizes the overall results obtained from this experimental work. All the methods are included with the corresponding value for maximum C_l and the stalling angle of attack attained.

Table 1
Effect of BLC on the maximum lift coefficient

NACA 0021	Maximum C_l	α_{Stall}
Without BLC	1.125	12
Suction	1.2	12
Blowing	1.2	14
Suction & blowing	1.33	14

4. Conclusions

NACA 0021 aerofoil model has been fabricated and tested in wind tunnel to investigate the effect of boundary layer control by method of suction and blowing on the aerodynamic characteristics of the aerofoil. The experimentation is carried out by measuring the pressure distribution along the upper and lower surface of the aerofoil to detect the exact location of flow separation. This separation point was then used as a reference to locate the boundary layer control. From the results attained, it was identified that the flow separation initiated at point 12 (at α = 12°, x/c= 0.55). The results showed that the flow separation occurred when there exists an adverse pressure gradient at which the pressure started to rise in the direction of the flow and the boundary layer tends to separate from the body surface. The outcomes of the tests also showed that the control setups by method of suction and blowing are very effective in controlling the airflow to avoid or delay separation. The stall angle of attack and maximum C_L increased to provide a better lift performance for the aerofoil. For the combined effect of both blowing and suction, the $C_{l\ max}$ increased to 1.33 (18.22% improvement) and the stall angle has been increased from 12° to 14°.

Acknowledgement

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