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Theoretical/Experimental Analysis of a Novel Airbreathing Device for Flow Control

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Since the first flight of the Wright brothers, there has been considerable effort devoted to improving wing performance. This research introduces theoretical and experimental study of a new novel method, a so-called airbreathing device (ABD), that provides simultaneous drag reduction and enhancement of lift. The basic principle of this technique is to introduce a transverse groove in the solid upper surface of the airfoil and an airstream is injected into one side of the groove and then completely removed from the other side. The direction of this secondary flow is essentially parallel to the main flow. The benefits of the device were found to depend on the air rolling velocity and the internal geometry of the ABD. This device appears to energize the main flow by transferring momentum to the weak fluid particles near the wall. Also, the pressure drop associated with the high speed of the flow inside the ABD is assumed to absorb some of the adverse pressure resistance. Theoretical and experimental results are presented. Potential sources of errors in the experimental results are discussed with recommendations for future work. The increase in lift and decrease in drag occur simultaneously, and up to 30% improvements were achieved.

Nomenclature

C = chord length of the airfoil
C_d = drag coefficient
C_i = ratio of airbreathing device (ABD) flow speed to freestream velocity
C_l = lift coefficient
H = height of the ABD
h = relative height of the ABD base
L_s = distance from the leading edge to the ABD
R = radius of the ABD base
S = width of the ABD
U_∞ = freestream velocity
u_i = injection speed
α = angle of incidence of an airfoil

Introduction

AERODYNAMIC flow control is aimed at improving the performance of lift surfaces. All of the methods used hitherto are ultimately aimed at achieving this. Thus, the desired goals of external flow control include separation/reattachment control, lift enhancement, laminar to turbulent transition delay, and drag reduction. These objectives are interrelated, and achieving a beneficial effect in one aspect may very well adversely affect another.

As an example, if the boundary layer becomes turbulent, its resistance to separation is enhanced, and more lift can be obtained at increased angle of incidence. On the other hand, the skin-friction drag for a laminar boundary layer can be as much as an order of magnitude lower than that for a turbulent layer. Thus, if transition can be delayed, lower skin friction is achieved. However, the laminar boundary layer can only support a very small adverse pressure gradient without separation, and subsequent loss of lift and consequent increase in drag occurs.

Another example is that in liquid flows heating is recommended to enhance the stability of the flow, but skin-friction drag will be simultaneously increased. Also an adverse pressure gradient can be used to minimize skin friction, but it promotes transition and separation.

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These examples point to potential conflicts because trying to achieve a particular benefit may adversely affect another area. An ideal method of control that is simple, inexpensive to construct and to operate, and does not have any adverse disadvantages does not exist. Therefore, there must be a compromise to achieve a particular design feature. Figure 1 is a schematic representation of the interrelationships between different flow control goals and techniques. In Fig. 1, the main techniques are listed in the middle of the diagram, and arrows point out the resulting advantage(s) from using the technique and the resulting disadvantage(s). Only the active techniques are listed in Fig. 1, but interrelationships also exist for the passive techniques. Chang[1] reviewed several passive and active methods that have been used to delay separation in both low- and high-speed flows. Extensive reviews were made by Roache,[2] who reviewed more than 1100 papers, and more recently by Fletcher.[3] Gad-el-hak[4] attempted to present a unified view of the methods. Bushnell,[5] Gad-el-hak,[6] and Bushnell[7] may be consulted for more details.

Scope of Present Work

The main objective of the present work was to create an air roller on the top of an airfoil section. Initially it was hoped to achieve this by the introduction of transverse grooves on the suction side of the airfoil.[8] To enhance the rolling action of the fluid inside the grooves, injection and suction were simultaneously introduced inside the groove. This air roller was restricted to a single groove, and the technique was patented and termed an airbreathing device (ABD). This method is original, and the current research presents the first reported use of the device. The ABD proved to be an efficient flow control technique, as will be seen later.

Principle of the ABD

The main purpose of the ABD is to introduce a groove in the solid surface perpendicular to the main stream flow direction, as shown in Fig. 2. Another fluid stream (with the same fluid as the main flow) is injected through one side of the groove and then sucked away from the other side. The direction of this secondary flow inside the ABD should be essentially parallel to the main flow, and the injected fluid should be completely sucked away in the suction. Consequently, the injection flow rate is equal to the suction flow rate.

The geometry of this groove can be varied, although the simplest form is a rectangular groove with a flat base. Optimizing the shape of the ABD would require extensive research and is largely outside the scope of this paper. The curvature of the base, the design of the

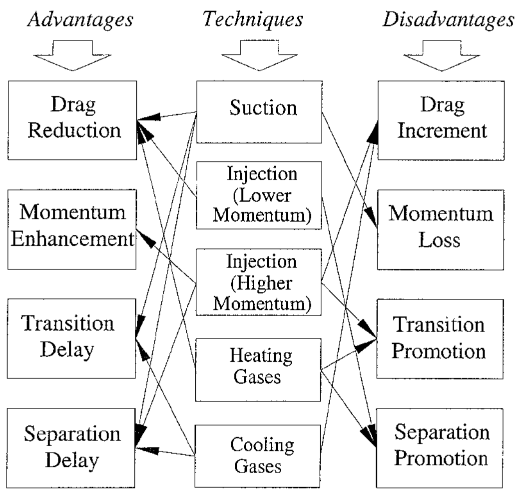
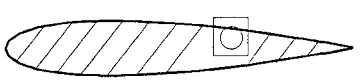
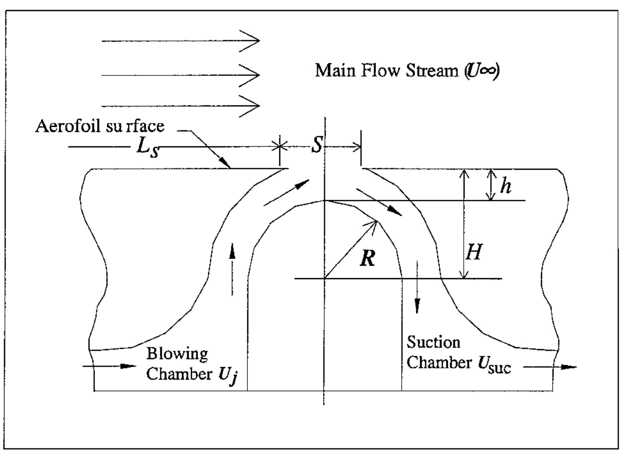


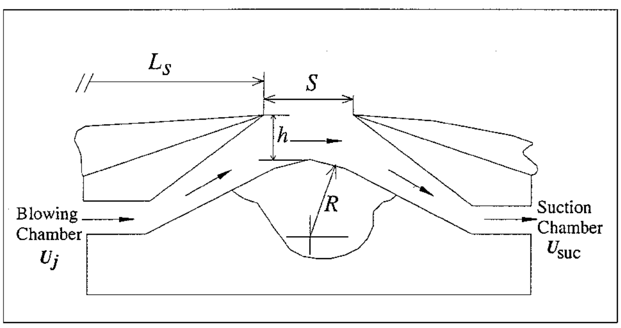
Fig. 1 Interrelations between the effects of different flow control techniques.



	Model 1	Model 2
L_s (cm)	5.7	5.7
S (cm)	0.5	0.6
R (cm)	0.5	2
h (cm)	0.5	0.6



Model 1



Model 2

Fig. 2 Schematic of roller ABD on the top surface of the airfoil.

inlet and outlet, the location of the device (relative to the leading edge), and the flow characteristics inside the ABD are all important parameters in determining the performance of the device. These parameters are interrelated so that extensive research is necessary to understand fully the behavior of the device.

Computational Modeling of the Problem

The commercial code FLUENT, which was designed to model fluid flow, heat transfer, and chemical reactions, was used in the present study. It incorporates up-to-date modeling techniques and a wide range of physical models for simulating fluid flow problems. The computer code solves the governing conservation equations. Closure and completeness of the governing equation set are achieved by means of models of the physical processes taking place within the calculation domain.

Modeling of the Airfoil with ABD

In general, modeling of the airfoil fitted with the ABD is similar to modeling of the smooth airfoil. However, introducing the ABD to the top surface of an airfoil needs two additional main steps.

1) Define the location of the ABD on the top surface of the airfoil.
2) Adapt the mesh to represent the ABD area.

Further details of this model can be found in the work by Al-Shihry.[9]

Theoretical Results Validation

One of the main objectives of the present study was to investigate theoretically the design parameters that influence the effect of the ABD on the flow. The computational fluid dynamics (CFD) simulation of the fluid-flow problem under investigation was compared with the experimental data to justify the CFD study. Two cases of a smooth airfoil and an airfoil fitted with the ABD were tested both theoretically and experimentally. The CFD results were found to be in reasonably good agreement with the experimental data. An example of this is shown in Fig. 3. Note that the general trend of the effect of the ABD on the performance of the airfoil is similar in both the theoretical and experimental results. This general agreement, which was obtained between theoretical and experimental results, provides confidence in the validity of the CFD simulation of the problem under investigation.

Theoretical Program

The number of parameters that can determine the characteristics of the ABD include the location of the ABD, L_s, the width of the

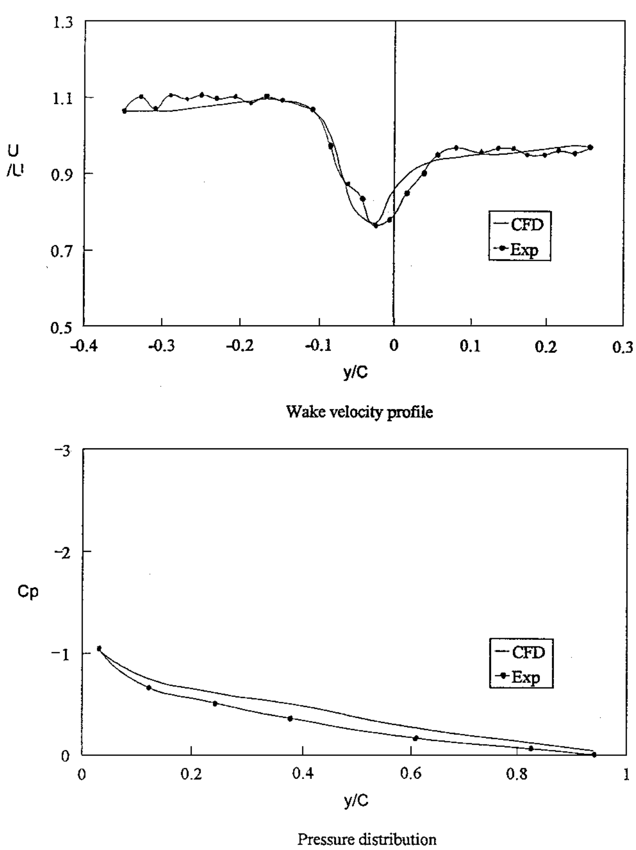


Fig. 3 Comparison of CFD calibration with experimental results for a smooth NACA0012 airfoil, U_∞ = 30 m/s, α = 4 deg.

ABD, S, the height of the ABD, H, the relative height of the curved base of the ABD, h, and the relative flow rolling speed inside the ABD, C_i.

Because the idea of an ABD was introduced for the first time in the present study, the general behavior of the device was first clarified before taking a further step towards optimization, which is currently being researched.

Experimental Program

The experimental program involved several phases. The smooth-airfoil case was tested to compare it with published data for the characteristics of a NACA0012 airfoil section. These data were used as a reference for the rest of the experiments. The airfoil was tested with the ABD fitted on its top surface. The two cases tested are shown in Fig. 2. Each experiment involved in the following measurements:

1) Lift and drag forces were determined using the three component balance.

2) Velocities throughout the wake region were measured using hot-wire anemometry and pitot tube traverses.

3) Pressure distributions were determined over the airfoil.

4) Flow visualization was conducted using smoke and tufts over the top surface of the airfoil.

These experiments were undertaken over a range of angles of incidence from −2 to 14 deg at 2-deg intervals. The freestream speed of the wind tunnel was 30 m/s.

The experiments undertaken in the present study were conducted in the 300 × 300 mm test section of a PLINT TE54 low-speed, open wind tunnel. The maximum air speed in this tunnel is 40 m/s, and the velocity profile is essentially uniform. The different geometries that were used for the ABD are listed in Table 1. The turbulence intensity of the flow inside the wind tunnel was measured using hot-wire anemometry. The value of this parameter is approximately 4%, and this is a relatively high level for this type of work. Control of the air speed is performed through a choking device downstream of the working section.

Sources of Errors

The experimental program undertaken was designed to provide adequate and reliable results. Despite that, every effort was made to achieve accurate results and that the results obtained compared well with published data, there are error sources that can affect the accuracy of the measurements. The main sources and the steps that were taken to minimize the effects are as follows.

The vibration of the wind-tunnel frame can affect the readings of the force balance and the hot-wire probe holder. Whereas performing these tests in a vibration-free test section can minimize this source of inaccuracy, this was not possible. Consequently, the effect of vibrations was minimized by measuring their frequencies and filtering them out of the signals.

Friction between the model and its supports can affect the transfer of the forces exerted on the airfoil to the load cells. Alternative arrangements for supporting the model can reduce this source of error. Different support arrangements are described in the published literature. Thus, performing the tests on three-dimensional or half-span models can produce friction-free results. However, in the present tests care was taken to minimize frictional effects by providing suitable clearances. Moreover, the effect of friction was also minimized because function exists for both the smooth construction and the airfoils fitted with the ABD so that the effect should be substantially cancelled out when the results of the two cases are compared.

Overall, despite these potential sources of error, the results obtained from the experimental program should be adequate in studying the benefits of using the ABD as a flow-control technique.

Table 1 ABD parameters for different modeled cases repeated at angles 4, 8, 12, 14, and 16 deg; $u_\infty = 40$ and $H = 0.5$ cm

Geometry	C_i	S, cm	L_s, cm	R, cm
10	1	0.6	8.7	∞
10	1.5	0.6	8.7	∞
10	2	0.6	8.7	∞
10	2.5	0.6	8.7	∞
20	1	0.8	8.7	∞
20	1.5	0.8	8.7	∞
20	2	0.8	8.7	∞
20	2.5	0.8	8.7	∞
30	1	1.0	8.7	∞
30	1.5	1.0	8.7	∞
30	2	1.0	8.7	∞
30	2.5	1.0	8.7	∞
40	1	0.6	6.2	∞
40	1.5	0.6	6.2	∞
40	2	0.6	6.2	∞
40	2.5	0.6	6.2	∞
50	1	0.8	6.2	∞
50	1.5	0.8	6.2	∞
50	2	0.8	6.2	∞
50	2.5	0.8	6.2	∞
60	1	1.0	6.2	∞
60	1.5	1.0	6.2	∞
60	2	1.0	6.2	∞
60	2.5	1.0	6.2	∞
80	1	1.0	6.2	0.03
80	1.5	1.0	6.2	0.03
80	2	1.0	6.2	0.03
80	2.5	1.0	6.2	0.03

Theoretical and Experimental Results and Discussion

Theoretical Results

As already mentioned the effects of air rolling velocity inside the ABD, location, width, height, and relative height of the curved base of the ABD on the wake velocity profile and drag and lift coefficients were studied in detail.[9] In this paper, only a sample of the results obtained will be shown.

Effect of the ABD on Wake Velocity Profiles

In an ABD, the injection flow rate should be equal to the suction flow rate so that the flow acts as a roller. The speed of the injected/sucked air inside the ABD is related to the main flow speed U_∞ via the coefficient $C_i = u_i/U_\infty$. As may be expected, it was found that increasing the relative ABD rolling speed C_i enhances the main stream flow directly. This behavior can be clearly seen in all results obtained. Figure 4 is representative of the results obtained. In all results, the wake velocity profiles were calculated at a distance of $0.13C$ downstream of the trailing edge of the airfoil. The results show how the magnitude of the minimum velocity in the wake is shifted to higher values as the relative rolling speed increases. This means that the tired flow in the wake region is energized so that wake recovery occurs over a shorter distance behind the airfoil.

The ABD was located on the top surface of the airfoil at a distance L_s from the leading edge. This distance was found to have a limited effect on wake recovery. The general trend obtained from the results was that the cases with smaller L_s often provided better performance than cases with high L_s because the minimum speed in the wake region is frequently higher for the cases of low L_s.

It was clear from the results obtained (Fig. 5) that the influence of the ABD on the airfoil flow is strongly affected by the width of the ABD. The near-wall fluid that flows tangential to the flow inside the ABD consequently becomes the part of the main flow that is most energized by the ABD. The transfer of energy from the ABD to this near-wall flow takes place through the interaction between the two flows. Accordingly, it can be said that as the area of interaction between the ABD and the main flow increases the energy transferred to the main flow will increase. This can be translated directly into a preference for higher values of S. This effect is clear with high values of C_i, that is, high relative rolling speeds, where an increase in the width S leads to larger minimum velocities in the wake. On the other hand, the larger the width is of the ABD, the greater is the interruption that will be caused to the main flow unless C_i is high enough.

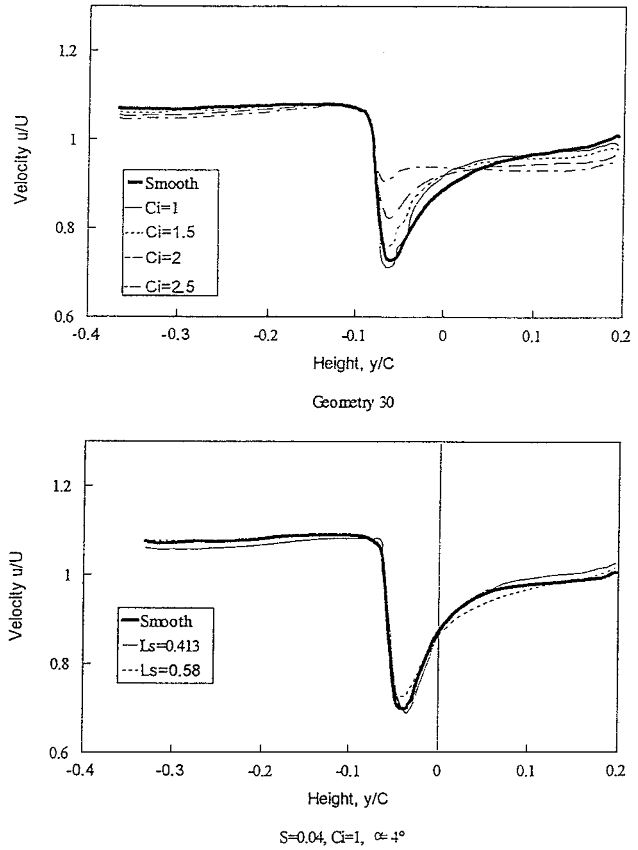


Fig. 4 Effect of C_i and location of the ABD on the wake velocity profile.

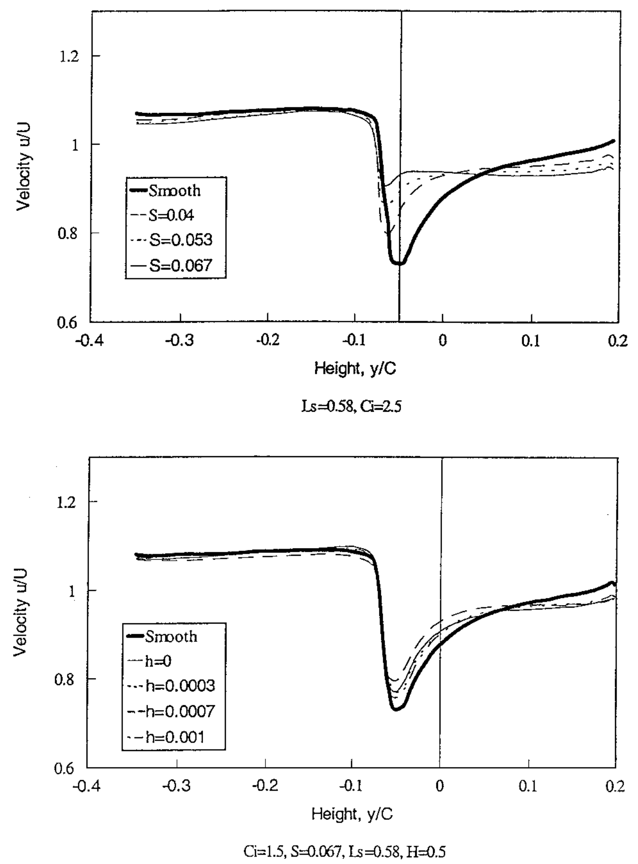


Fig. 5 Effect of the width and the relative height of the ABD on the wake profile at α = 4 deg.

The height of the ABD, H, is a very important parameter because it determines the amount of the flow that should be injected into and removed from the ABD. For a given value of C_i, a large height results in a higher flow rate, and consequently, higher power is required to drive the ABD. For a small values of height, less power is required to provide the same value of C_i. However, below a minimum value of H, the injected air could be choked so that the power consumption will increase with no corresponding increase in C_i.

From another point of view, it is preferable to keep H as small as possible to reduce the geometrical obstruction to the main flow and to extend the applicability of the technique to small-size airfoils. Nevertheless, the injection holes or slots must be manufactured so that the upper tip is as small as possible. The best configuration of the ABD is one in which the flow virtually occupies all of the height on both the injection and suction sides. The problem of minimizing the influence of the tip of the ABD is similar to problems found in the injection technique.[10]

Over the range simulated in the present research, it was found that that changes in H have little effect on the minimum wake velocity. This result indicates that the volumetric flow rate inside the ABD is relatively unimportant, and it is the rolling speed, that is, C_i, that is the dominant factor. More detailed study may be necessary to clarify the effect of the H on the performance of the device.

One of the parameters that was found to be of a particular interest and can play an important role in the influence of the ABD on the main flow is the relative height of the base, h (Fig. 5). Most of the cases examined in the theoretical study were for a flat base. However, the interaction between the main flow and the flow inside the ABD was found to be affected by the shape of the base of the ABD. If this base has a convex shape, the flow inside the ABD is forced to interact with the main flow more strongly, so that more energy is transferred to this main flow. However, if the curvature is too high, then the angle of injection will be increased to such an extent that the main flow may be badly interrupted, and separation may occur as a result at the location of the ABD. Another problem associated with high convex radius of curvature of the base of the ABD is that all of the injected flow may not be entrained into the suction side, that is, the rolling action of the device will no longer be satisfied. This is due to the high inertia of the injected flow. This effect is likely to promote separation because this is usually associated with the normal injection technique.[11]. In the light of the preceding discussion, it would appear that optimization of the relative height is necessary to balance the two conflicting effects. It is likely that there is a certain range of curvature that can provide a strong interaction between the two flows inside and outside the ABD without adversely interrupting the main flow.

The results obtained appear to support this argument to certain extent. At an angle of incidence of 4 deg, it was found that the optimal relative height $h = 0.0007$. However, the effect of changing h is less clear at a higher angle of incidence of 8 deg. A convex base was used in the experimental cases to attempt to obtain a better performance from the ABD.

Effect of the ABD on the Drag Coefficient C_d

Generally, it was found that as C_i is increased C_d decreases. However, for lower values of C_i, for example, $C_i = 1$, there is an initial increase in the drag so that the value of C_d is often higher than that in the smooth case. The reason for the poor performance of the ABD at $C_i = 1$ is that the ABD at this speed ratio is not able to compensate for the geometrical drag penalty. This result of an initial increase in drag agrees with the effect of C_i on the velocity profile in the wake region. A representative of the results obtained can be seen in Fig. 6.

It can be deduced from the results that a larger width S generally results in a lower C_d. In virtually all cases, the greater drag reduction was obtained with $S = 1.0$. This may be due to the larger distance over which the two flows interact with each other so that more energy is transferred to the main flow. Choosing an appropriate value of the width S of the ABD was found to affect markedly the efficiency of the device. As an example, changing the value of S from 0.6 to 1.0 can increase the reduction in drag coefficient from 4 to 30% of

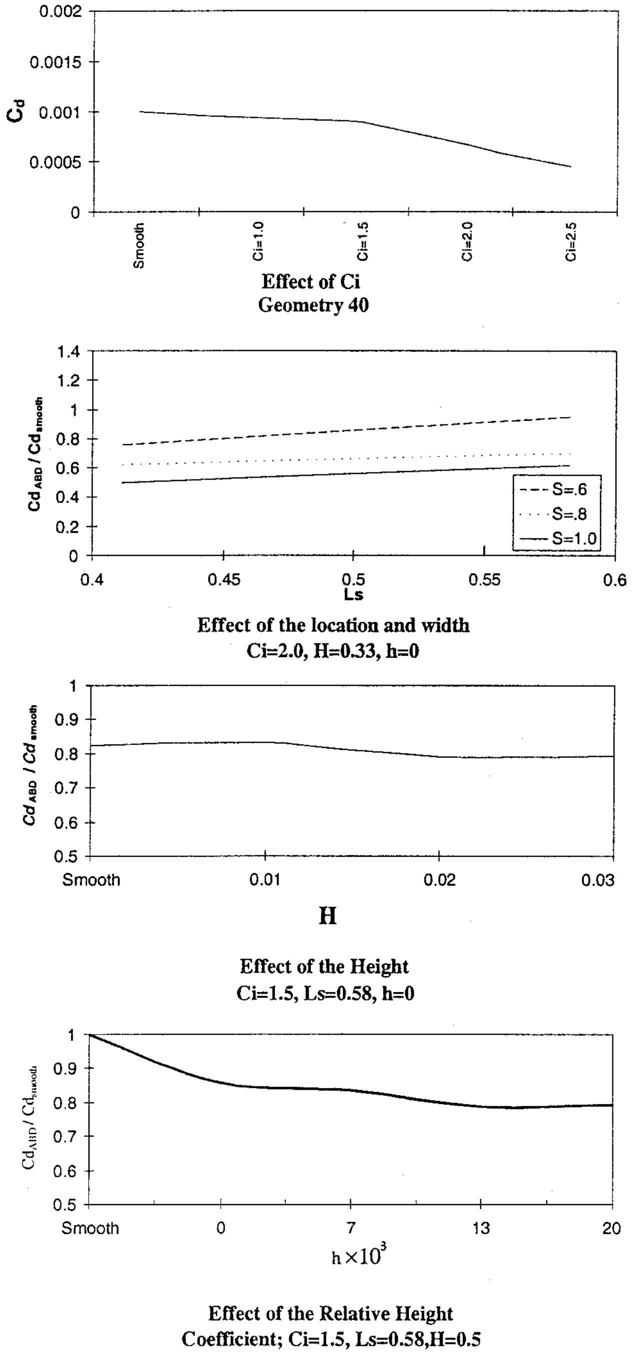


Fig. 6 Effect of C_i, location width, height, and the relative height on the drag coefficient at α = 4 deg.

the smooth case value. It was also found that lower values of L_s generally resulted in greater reductions in drag coefficient, although the range of ABD positions that was simulated is very limited at present.

Figure 6 also shows the effect of changing the height of the ABD on the values of C_d. The results obtained showed that there is an optimum value of H within the range tested at which the ABD has the best efficiency. The effect of changing the curvature of the base of the ABD on the drag coefficient is also shown. Changing the geometry of the base of the ABD has a significant effect on the performance of the system. The effect of changing the radius of the base is somewhat different at different angles of incidence. For example, the reduction in drag at $h = 0.0013$ dropped from about 20% at $\alpha = 4$ deg to around 10% at $\alpha = 8$ deg. In both cases, it was found that larger values of relative height appeared to be beneficial.

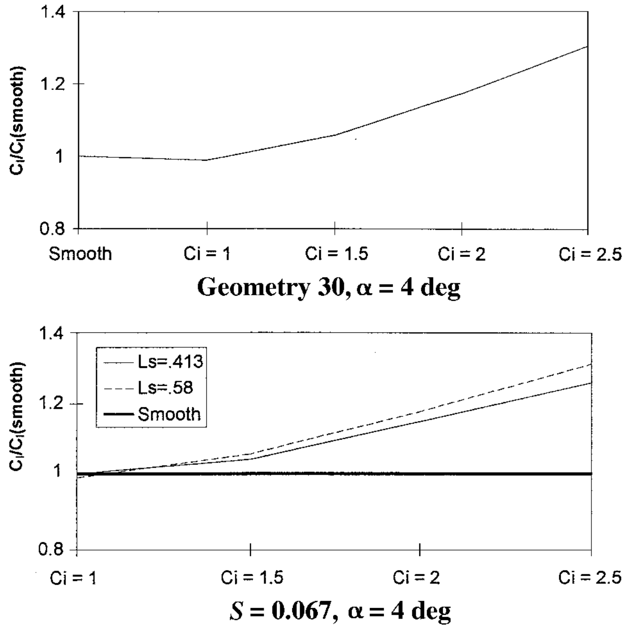


Fig. 7 Effect of C_i and location of the ABD on the lift coefficient at α = 4 deg.

Effect of the ABD on Lift Coefficient C_l

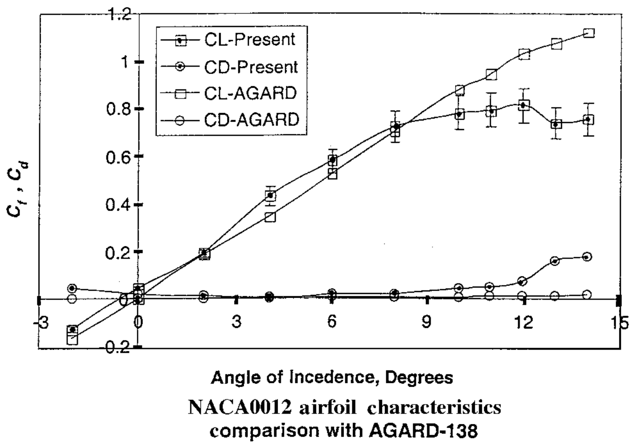
Controlling the main flow by using the ABD showed substantial promise in terms of increasing the C_l of an airfoil. All of the results obtained showed that increasing C_i can increase C_l significantly. When $C_i = 1$, however, the lift coefficient is lower than that of the smooth case. Increasing C_i up to a value of 2.5 can increase C_l by up to 30% depending on the geometry of the ABD and its location (for example, see Fig. 7). The lift coefficient was calculated by integrating the pressure coefficient C_p over the chord of the airfoil.

In a preceding section, it was found that the lower values of the L_s gave greater reductions in drag coefficient C_d. The optimal position of the location L_s depends on the values of S. For small values of S, the lower value of L_s provides better performance, whereas for some of the larger values of S, it appears that higher values of L_s are better. There is a certain value of $S = 0.058$, in the middle of the values tested, at which changing L_s has very little effect.

Experimental Results

Lift and Drag Force Measurements

The experimental measurements of lift and drag forces and, consequently, C_l and C_d were performed by means of the load cells on the balance system. The load cell signals were triggered at a frequency of 5 kHz, at a rate of 3000 samples per point. Each experiment was repeated at least five times at each angle of incidence. The choice of these values was made after a series of preliminary experiments that were conducted to determine the conditions under which the readings were independent of frequency and number of samples. The low frequencies caused by the vibration of the test section of the wind tunnel were measured and, hence, isolated from the final readings. The smooth airfoil, cast in the laboratory, was tested in the wind tunnel, and the results were compared with the characteristics of the NACA0012 airfoil published in AGARD 138, Thibert et al.[12]; Fig. 8 shows this comparison. For the present airfoil, it was found that 12 deg is the angle of maximum lift, α_{max}, whereas the corresponding AGARD value is 14 deg. This difference may be related to the higher level of flow turbulence and to the higher level of vibrations in the current test section. These factors are thought to promote trailing-edge separation at lower values of α_{max}. Generally, there is a reasonable agreement up to an angle of incidence of 10 deg, although the performance of the present airfoil deteriorates substantially at higher angles. Despite these differences, the present smooth airfoil results were used as a comparison.



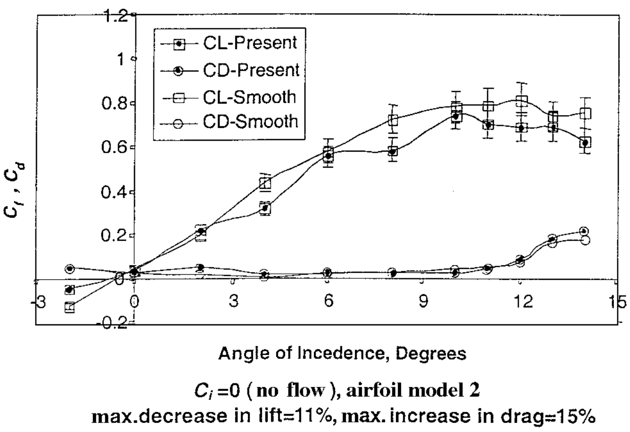
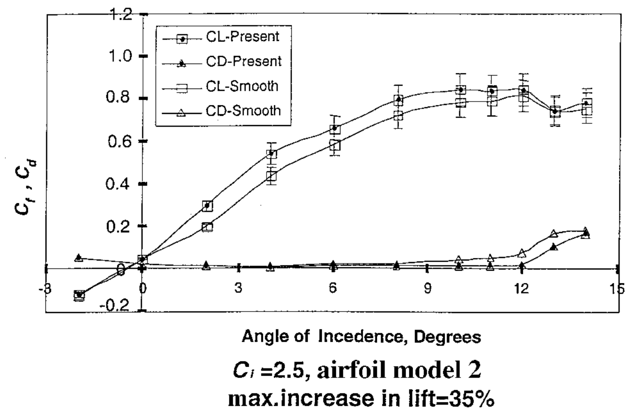


Fig. 8 Characteristics of the NACA0012 airfoil without ABD and with fitted ABD at no-flow condition.



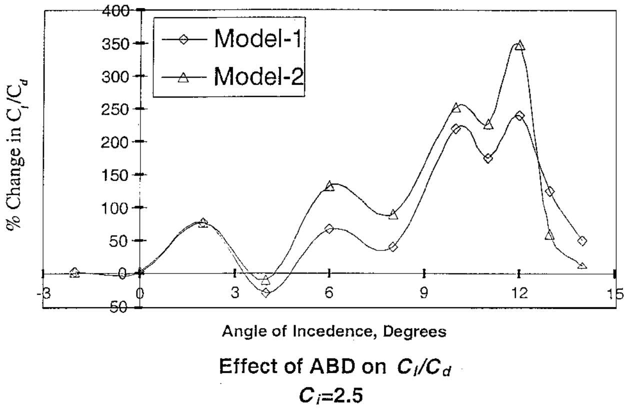


Fig. 9 C_l and C_d distribution C_l/C_d for the NACA0012 airfoil with and without fitted ABD.

The effect of the ABD on the top surface of the airfoil without any airbreathing flow for models 1 and 2 (Fig. 2) were studied. The drag was found to increase by up to 15% at some locations, and the lift decreased by 11%. This result is expected because the ABD with no flow behaves as a cavity, and this is known to cause some interruption to the main flow as a result of the loss of some fluid energy due to the induced circulation in the ABD. The deterioration in the performance of the no-flow ABD is not sufficiently large to lead to stall of the airfoil especially at lower to moderate angles of incidence. This is an important feature in practice and means that if the flow inside the ABD ceased for any reason the airfoil will still produce a sufficient amount of lift.

The effect of C_i on both C_l and C_d for models 1 and 2 were investigated. An example of the results obtained is shown in Fig. 9. From the results obtained, C_l is clearly enhanced by increasing C_i. An increase in lift of up to 35% was obtained, and the drag coefficient, in general, decreases especially at higher angles of incidence, α. This reduction in drag at higher angles of incidence means that the stall point is postponed, hence giving the airfoil a wider range of operation.

The effect of C_i on the C_l/C_d ratio for all cases was investigated. Figure 9 shows an example of the results obtained. Good enhancement can be seen on this ratio over most of the operating range of the airfoil. This enhancement increases with increasing C_i. The ratio C_l/C_d is an important parameter that indicates the performance of the airfoil by combining the individual changes in C_l and C_d. This does not contradict that achieving improvement in either of these two parameters, C_l or C_d, is a valuable advantage of the ABD technique. Fortunately, both parameters were improved simultaneously for most of the range of operation of the airfoil.

The performance of model 2 was, in general, better than that of model 1. This is may be due to the larger value of the width of the ABD, S, in model 2, which provided more interaction to occur between the main flow and the flow inside the ABD. From the geometry of the two models, it is clear that the flow inside the ABD is smoother in the case of model 2 than that of model 1. In model 1, the flow has to change direction through an angle of almost 180 deg inside the ABD piping, whereas in the case of model 2, the flow changes direction only slightly before it exits the ABD. Careful design of the internal structure of the ABD should enhance its performance.

Wake Flow Measurements

By the use of a traverse system, it was possible to scan the wake region downstream of the airfoil with X hot-wire probe to measure the velocity profile. The width of the wake and the minimum value of the wake velocity both determine the amount of loss in momentum of the flow caused by the presence of the airfoil in the flow. Consequently, reducing the width of the wake and/or increasing the value of the minimum wake velocity means that the flow is enhanced and the drag is reduced.

The readings from the X hot wire were taken by 3000 samples at every point at a frequency of 10 kHz. The average readings were then considered. The experiments were repeated at least five times to check the repeatability. As a checking procedure, different frequencies were tested, and it was found that the frequency of 10 kHz gave almost the same results as measurements taken at higher frequencies (up to 40 kHz) over the same period.

The velocity profile behind the airfoil was found to change with C_i. The higher was the value of C_i, the greater was the enhancement in the wake region. It was also clear that for lower values of C_i, the wake width was increased, although it was always narrower than that for the smooth airfoil. Figure 10 is an example of these results.

The results obtained seem to indicate that some of the momentum in the outer region of the wake is pulled into the inner region. This may not necessarily reduce the drag coefficient, but the lift of the device will be increased due to the higher circulation around the airfoil; more important, the flow on the top surface will be more capable of resisting separation. The pulling of the higher momentum flow to the wake region can be seen where the velocity at the outer

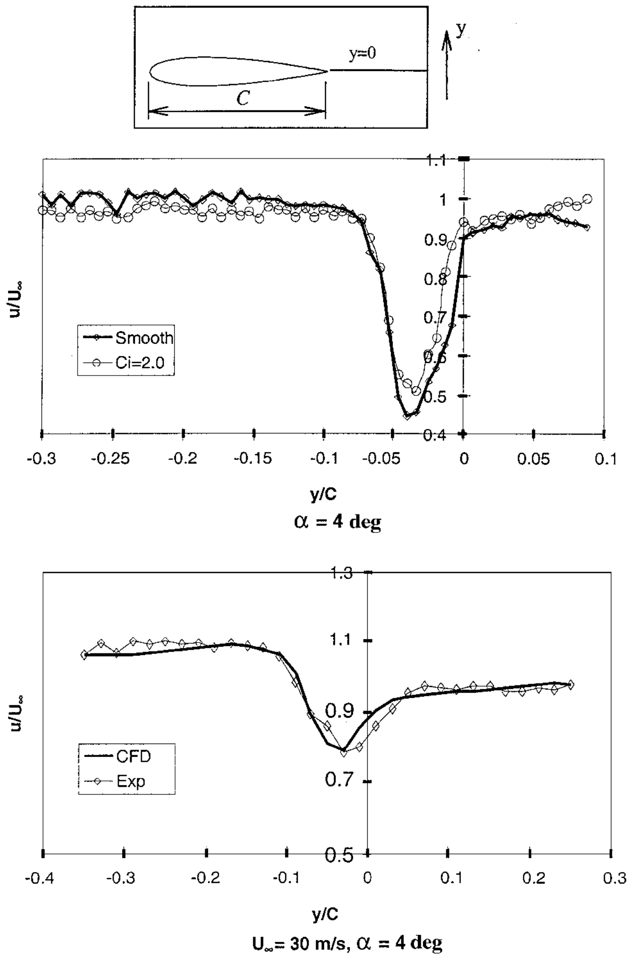


Fig. 10 Effect of C_i on the U velocity profile at α = 4 deg and velocity profile in the wake of a smooth NACA0012 airfoil, U_∞ = 30 m/s, α = 4 deg.

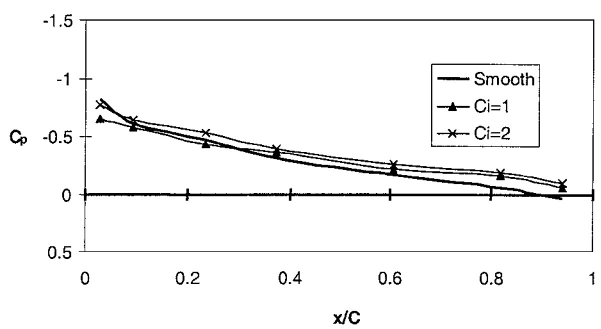


Fig. 11 Pressure distribution over the NACA0012 airfoil with and without the ABD α = 4 deg.

region of the wake, that is, for $y/C < -0.1$ and $y/C > 0.0$ is lower in the case of the airfoil with the ABD than that of the smooth airfoil.

Pressure Distribution

It was possible to measure the pressure distribution over the airfoil of model 2 with and without the ABD fitted to its top surface using pressure tapping. The ABD had a favorable effect on the pressure distribution over the airfoil. An example of the results obtained is shown in Fig. 11. In the results obtained, it was clear that the ABD was able to absorb some of the adverse pressure over the top surface of the airfoil, which gave high suction pressure. This is thought to be due to the drop in pressure associated with the relatively high speed in the rolling flow inside the ABD. This drop in pressure is sensed in the region upstream of the ABD. It is this improvement in pressure distribution that is responsible for increasing the lift of the airfoil because the lift is linearly proportional to the area under the curve of C_p. It was not possible to measure the pressure in the region of the ABD, and, therefore, the curves do not show any details about the pressure in the region of the ABD. However, it was possible to predict the change in pressure inside the region of the ABD by theoretical simulation.[9] Both theoretical and experimental studies showed that the pressure distribution after the location of the ABD is better than that of the case of smooth airfoil.

Flow Visualization

Flow visualization using two methods, smoke lines and tufts, was obtained. Tufts photographs are thought to give more accurate representation of the effect of the ABD on the main flow. The remarkable effect of the ABD on the flow can be seen in Fig. 12 at the incidence angle of 14 deg, which is well within the stall region of the smooth airfoil. It was observed from the results that the flow is attached to the surface of the airfoil for the cases at which the ABD is off up to 8 deg. This is clear evidence that the main flow is not largely interrupted by the existence of the ABD, especially for moderate angles of incidence. When the ABD is on, the attachment of the flow to the surface is ensured, as can be seen from Fig. 12. The airfoil is found to experience a separation as the angle of incidence exceeds 12 deg. The separation occurs at the trailing edge, as was clear from the tufts pattern. With ABD on, the separation was delayed, and the tufts showed that the flow is still attached even at higher angles. In the case of 16 deg, the adverse pressure was so large that the ABD could not prevent separation, and, therefore, the tufts were still reversed. It was not possible to test experimentally more than one ABD, but in theoretical study, it was found that locating two devices could prevent separation even at the high angle of incidence of 16 deg.

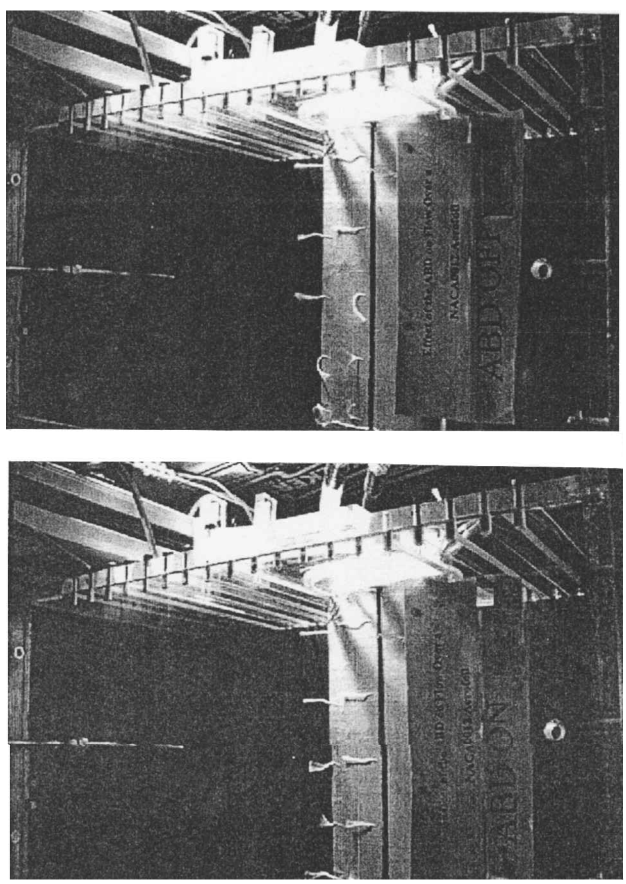


Fig. 12 Flow visualization using tuffs over the airfoil with the ABD off and on at α = 14 deg.

Conclusions

This research has introduced the idea and the use of a new active technique, ABD, to control the flow over aerodynamic devices.

The performance of the ABD was tested theoretically and experimentally. An accurate model of an airfoil with the ABD fitted on its top surface was formulated. Thus, it was possible to calculate the pressure distribution, wake velocity profile, the lift coefficient, the drag coefficient, and the other flow parameters in the computational domain.

The ABD was tested using a NACA0012 airfoil section, which was manufactured and tested in a low-speed wind tunnel. The experimental program included X hot-wire measurements of the flow velocity, direct measurement of the aerodynamic forces (lift and drag) and pressure distribution, and also flow visualization using smoke and tufts. By analyzing the results, which were obtained from both the experimental and theoretical program, it is clearly possible to conclude that using the ABD as a flow-control technique proved to be an efficient and practical method of enhancing the performance of an airfoil wing section. Reduction in profile drag as well as increase in lift were obtained. The theoretical results were found to be very promising and, furthermore, were in good agreement with the experimental data. Reduction in profile drag (up to 19%) was achieved, and, therefore, operating cost will be expected to reduce accordingly. Lift was also enhanced (up to 30% for higher C_l), which means achieving a higher lift at lower angles of incidence. The onset of the stall point was delayed due to delay of the trailing-edge flow separation at high angles of attack. The authors believe that the ABD can also be used in many other applications where reducing the boundary-layer thickness δ and drag coefficient C_d is required.

Because the proposed ABD is novel, much more work should be done to obtain a complete understanding of its performance in different applications. Thus, a more comprehensive study should be undertaken both theoretically (using CFD) and experimentally.

On the theoretical side, in addition to optimization of the geometry of the ABD, different applications can be studied such as projectiles, fuselages, wind-tunnel walls, airbreathing machinery, pipe flows, marine applications, etc. The different boundary conditions for each of these applications is expected to require different internal designs and characteristics for the ABD, but the improvements are expected to be significant.

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