Review analysis on laminar separation bubble at low Reynolds numbers

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Abstract. The importance of drag reduction with separation bubble become necessary study on air and ground vehicles, gas turbines, etc. and therefore their presence will play a major role in this context. Normally laminar separation bubble found to exist on the suction side of low-pressure turbine and this phenomenon can be reduced by vortex generators. In this review paper some findings show that the rate at which the decrease in lift coefficient because of the formation of laminar separation bubble is less compared to the increase in the drag coefficient, and at higher angles of attack separation bubble burst found to cause stalling of aerofoil. This paper further discusses how the length of the separation bubble is independent of the angle of attack even though the laminar region of the separation bubble found to extend. Further we report the impact of varying the angle of attack on the characteristics of the laminar separation bubble and how blowing and suction control mechanism suppresses the separation bubble.

Keywords: Laminar flow separation, Reynolds number, Separation bubble, stall behaviour

1. Introduction

Laminar separation bubble has formed when free stream decelerates that could not attach to the airfoil surface further because of the increment in the adverse pressure gradient which is predominant in the lower Reynolds number region, i.e. Re < 10⁵, and leaves the surface to become free shear layer. Later it could go through transient, then change to turbulent and finally may reattach with the surface. This causes the inability of the boundary layer to make an early transition to turbulent flow, instead the laminar flow separates before the transition inability and it may also lead to the formation of a long bubble when the viscous force becomes more severe than the inertial force. Therefore, the shear layer may not reattach to the upper surface of an airfoil and long bubble might be the result of short bubble burst or it may become the shear layer without attaching again. Since a long separation bubble leads to substantial trailing edge loss, smaller the size lesser will be the loss.

The performance of low Reynolds number airfoil strongly depends on the location of transition. This condition sets the length of the laminar separation bubble and consequently the magnitude of the drag rises because of the presence of the bubble. The controlling transition is
a major step towards reducing the adverse effects of separation bubble on the airfoil surface for low Reynolds number. Fig. 1 illustrates the structure of separation bubble on a curved surface.

![Diagram of separation bubble](image)

**Figure 1.** Formation of laminar separation bubble

2. **Scientific background and prior research on Laminar separation bubble**

As the Reynolds number reaches a particular value, the formation of separation bubble is on the suction side of the airfoil and the separation occurs at higher adverse pressure gradient, and reattachment of the separated shear flow becomes unstable. This action takes place when sufficient energy is to maintain the circulatory motion and further bursting of the bubble leads to leading edge stall [1]. In case low Reynolds number airfoil with higher angle of attack, the reattachment of turbulent boundary layer may not occur and the laminar separation bubble extends up to the wake of the airfoil causes of decrement in lift and increment in drag thus giving rise to the abrupt stall. It can be controlled by an early transition of the boundary layer before separation by modifying the airfoil surface, vortex generator, strips, groove, etc.

Two kinds of bubbles formed namely short bubble and long bubble. The short bubble is enclosed in between the separation and reattachment points whereas the separated flow may reattach at the trailing edge. The presence of a short bubble is possible only for a certain range of Reynolds number that depends on the surface pressure distribution, airfoil surface profile, irregularities in surface and turbulence of the free stream.

The airfoil performance regarding decrease in Reynolds number was initially analyzed by Schmitz [2]. He conducted experiments on few objects, namely a thin flat plate, thin cambered plate, and a conventional N60 airfoil within a Reynolds number ranging from $2 \times 10^4$ to $2 \times 10^5$. He found out airfoils are prone to separation at low Reynolds number range of $10^4$ to $10^5$, where these flat plates work better for this particular range of Reynolds number. The experiments further conducted by Selig et al. [3] on a range of low-Reynolds-number airfoils and concluded that $C_{max}$ increases with higher Reynolds number. Further investigation by Selig on 60 sailplane-type airfoils revealed that the drag-polar was plainly similar and almost insensitive to the Reynolds number variations more than $10^5$. Gaster [4] founds that laminar separation
bubble depends on Reynolds number and later Meara and Muller [5] found that separation bubble size decreases with the increase in Reynolds number. The height and change in length of separation bubble were investigated by Diwan and Ramesh [6] and found that height increases a faster rate than length of separation bubble.

3. Laminar separation bubble on aerofoil surface
Fig. 2 shows the separation bubble formation on the airfoil surface. The laminar separation bubbles are widely regarded as parasite and have a typical effect of decreasing lift hence it decreases the aerodynamic efficiency. The performance of an airfoil would be limited when the boundary layer separates quickly at low Reynolds number. Airfoils in the micro air vehicles, the unmanned aerial vehicles working in the Reynolds number range of $10^3$ to $10^6$ and airfoils in wind turbine which work in the Reynolds number range of $10^5$ to $10^6$ are subjected to laminar separation bubble. From the prior investigations we found that physical dimensions of laminar separation bubble depends on Reynolds Number, outer disturbances and angles of attack. The laminar separation bubble mostly happens in the Reynolds number range ($60,000 < \text{Re} < 500,000$) and before the stalling angle [7]. As the Reynolds number increases, the bubble size decreases, and the position of laminar separation bubble also moves ahead with the higher angles of attack.

![Figure 2. Laminar separation bubble on airfoil](image)

4. Numerical investigations on LBS
From the numerical analysis by Genc and Kaynak [8] on NACA 2415 airfoil making the use of blowing and suction, the results with $K-\omega$ SST transition model show that the subsided separation bubble moves upstream with the pressure hump. Since there are no experimental work with blowing and suction for this airfoil, quantifying the amount of change was not possible for blowing or suction but it has been judged on the qualitative grounds that the effects of blowing energize the flow and therefore eases the expansion of laminar separation bubble. Finally, it has been concluded that the control mechanism of suppressing the bubble becomes evident with blowing or suction, and thus the possibility of reducing the upper surface pressure coefficients to increase the lift and to decrease the drag were possible.

These findings further have been analysed using transition models for various jet angles, velocity ratios and locations. It is quite interesting to note that very little blowing result seems
to be good and greater blowing velocity ratios are not dependent on the blowing locations, and on the other hand suction results are quite opposite and therefore the earlier numerical predictions are quite consistent with the above results. Based on the analysis of streamline indeterminacy and velocity profile for the same airfoil, the results shown that the 3% of the airfoil chord reduces the laminar regions due to suction or blowing, and boundary layer velocity profile found in the same location also supports these results.

5. Experimental investigations on LSB

5.1. Investigation of Hui and Yang

The experimental investigation on GA (W)-1 airfoil and the results of Hui and Yang [9] have been further analyzed. We focused to investigate the changes happening in pre-stall regarding the Laminar Separation Bubble. From this analysis, it has been understood that the airfoil’s boundary layer would strongly get attached all the way from leading edge to trailing edge over the upper surface when the adverse pressure gradient comparatively is at lesser angles of attack($\alpha<6^\circ$).

It is understood that increase in drag coefficient would be negligibly small within the above mentioned angles of attack range. An increment in the lift coefficient is almost found to be the same as that of thin airfoil theory within the specified angle of attack, and no sign of forming the Laminar separation bubble.

From the theory we have understood that the laminar boundary layer will not resist the rise of adverse pressure gradient. The separation from the upper surface of the airfoil would become the starting point for the separation bubble region.

The findings further states that Laminar Boundary layer has reattached in the airfoil’s upper surface as the starting point of the turbulent boundary layer happens after the region of transition between the angles of attack, $8^\circ<\alpha<12^\circ$, and this is the region where separation bubble formed on the upper surface of an airfoil. From the investigation, an increased rate of lift coefficient begin to degrade considerably with the increasing angles of attack. This is because of the formation of the laminar separation bubble, and the drag coefficient was begun to rise faster as the angle of attack increases.

The investigation additionally states that the separation will burst for $\alpha>12^\circ$ as soon as the adverse pressure gradient becomes noticeable, and reattachment of the separated boundary layer on the upper surface becomes negligible. Further, the extensive flow separation begins to happen over the whole upper surface, and the airfoil was found to undergo the stalling condition for the same. Also, an increase lift coefficient and decrease in drag coefficient becomes significant as the angle of attack increases.

5.2. Experimental investigation by Yang and Hui

Yang and Hu [10] performed the experimental investigation on the upper surface of an airfoil. The surface pressure distribution was begun to vary notably for various angles of attack. The profile of the surface pressure coefficients has reached the negative peaks rapidly for the angle of attack, $\alpha<8^\circ$ when it is very near to the leading edge of an airfoil. Then the recovery of surface pressure distribution occurs slow and steadily over the upper surface up to the trailing edge of an airfoil.

As the angle of attack increases from $8^\circ$ to $12^\circ$, an important feature of almost a constant pressure region has been observed, and a region of pressure plateau was identified for the sudden increase of surface pressure coefficient. The recovery surface pressure set up in the downstream direction was gradual and smooth, and also at comparatively low angles of attack. This feature leads to the laminar separation bubbles formation with the airfoils having low Reynolds number.

Based on the theoretical model developed by Horton & Russell, they characterized the airfoils having low Reynolds number for the formation of laminar separation bubble. A model has been
introduced with two portions, namely laminar and turbulent to an airfoil with low Reynolds number for the formation of laminar separation bubble. This is to imply the location of separation point of the laminar boundary layer on the airfoil surface and to show the starting point of the pressure region.

Further investigation showed that upper surface pressure found to be almost constant and magnitude of the negative surface pressures has reduced significantly at $\alpha \geq 12^\circ$. And this result reveals that broad range of flow separation occurred over nearly the whole airfoil upper surface and stalling condition has been reached for the same angle. The investigations by using the PIV system gave more information’s about the laminar flow separation for the transient behavior. PIV measurements used for visualizing the global feature on the airfoil for the formation of laminar separation bubble at $\alpha = 10^\circ$. From the PIV measurements, it has explained that the laminar boundary layer forms as a thin vortex layer attaching to the surface of an airfoil. The expected result of boundary layer attaching to the upper surface of an airfoil near the leading edge also explained by PIV techniques.

PIV measurements could not show clearly that bursting of the separation bubble causes an airfoil to stall for $\alpha > 12^\circ$ where the adverse pressure gradient becomes very aggressive. From the measurements it is found that the laminar boundary layer separates from the upper surface of an airfoil close to the leading edge and transits to the turbulent condition quickly. The boundary layer separated from the upper surface of an airfoil noted to be raised and thrown away from the upper surface because of the severe adverse pressure gradient.

Another experiment conducted for different reference speeds [6] shows that the increase in length and height of the bubble decreases with reference speed and size of the bubble has been quantified with the aspect ratio. Further it is stated that reasonable collapse happens for the increase of aspect ratio and decreasing Reynolds number, and concluded that the increase in the bubble’s height with a greater rate and a decrease in Reynolds number with the corresponding change in length.

6. Conclusion

From the review analysis, it may be concluded that complete elimination of the laminar separation bubble is not possible but it may be reduced to an accepted level. By suitable modifications on the top side of the airfoil, the bubble burst and vortex shedding because of laminar separation bubbles at a higher angle of attack may be delayed or avoided. Experimental investigations need to be done on the analysis of an abrupt stall on the airfoil surface for low Reynolds numbers. During the study of control over the laminar separation bubble with vortex generators, no structural limitations for the design have been considered. An extensive structural analysis may be performed.

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