Experimental Investigation of the Structure and Dynamics of Laminar Separation Bubbles at the Onset of Bursting
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A two-dimensional laminar separation bubble on a flat plate is studied experimentally using Particle Image Velocimetry (PIV) and flow visualization. The separation bubble was generated on a flat plate by an imposed adverse pressure gradient. The adverse pressure gradient was generated by using an inverted wing with a NACA 643-618 airfoil mounted above the flat plate. A parametric study of the effect of the upstream flow velocity and the induced pressure gradient on the mean flow topology and the unsteady behaviour of the separation bubble was carried out in the low-speed water tunnel of the Hydrodynamics Laboratory at the University of Arizona. The structure and dynamics of the laminar separation bubble were found to depend strongly on the aforementioned parameters. As the flow velocity is reduced, at very low flow velocities the bubble is seen to undergo a drastic change in geometry, resulting in bubble bursting. An attempt is made in this work at understanding the physics of bubble bursting. For certain flow conditions, strong vortex shedding near the reattachment region of the bubble was observed, which is a characteristic behaviour of short bubbles. High-resolution spatio-temporal PIV measurements were made to analyze the formation and breakdown of these flow structures.

Nomenclature

\[ l \] = Separation bubble length
\[ h \] = Separation bubble height
\[ x_s \] = Separation location
\[ x_r \] = Reattachment location
\[ H \] = Height of airfoil above flat plate
\[ \text{AoA} \] = Angle of attack of the airfoil
\[ C \] = Chord length of the aerofoil
\[ f \] = Frequency of vortex shedding
\[ U_\infty \] = Test section inflow velocity
\[ St \] = Strouhal number
\[ X_{AF} \] = Distance between aerofoil and the flat plate leading edge
\[ T_u \] = Turbulence intensity
\[ P \] = Pressure-gradient parameter
\[ Re_{SS} \] = Separation Reynolds number
\[ \alpha \] = Angle of attack
\[ \theta \] = Boundary-layer momentum thickness

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I. Introduction

Laminar separation bubbles are prevalent in a wide range of engineering applications such as the leading edges of thin airfoils, hydrofoils, Micro Air Vehicles (MAV’s), Unmanned Air Vehicles (UAV’s), turbomachinery flows, wind turbines etc. Attention is focussed mainly to their effect on airfoil related flows because of the importance for an accurate prediction of lift and drag. Flow separation involving laminar separation bubbles occurs when the laminar boundary layer reaches the separation point before transition to a turbulent layer is reached. This happens at a certain combination of angle of attack ($\alpha$), Reynolds number and turbulence level ($T_u$) of the free-stream. The development of flow downstream of the separation point depends on the behaviour of the separated shear layer. Transition to turbulence occurs shortly after the separation point, due to the high instability of the shear layer, thereby increasing the entrainment with the external flow. This causes the flow to reattach to the surface and form a region of relatively stagnant flow, which is also known as a separation bubble. A schematic of a time-averaged laminar separation bubble is shown in Fig.1. At low Reynolds numbers or at very high angles of attack the flow may be unable to overcome the imposed adverse pressure gradient and fail to reattach or form a very long bubble. This flow separation can lead to massive degradation of aerodynamic performance characteristics and aircraft stability. Due to the hydrodynamically unstable nature of the separation bubbles, the boundary layer undergoes transition to turbulence even at low Reynolds numbers.

![Figure 1. Section view of a laminar separation bubble (from Mayle31)](image)

Laminar separation bubbles and their impact on airfoil stall were first studied by Jones1. Bubble behaviour close to stall conditions were studied by Gault2 and McCullough & Gault3. This led to the introduction of a distinction between leading edge stall, trailing edge stall and thin airfoil stall. The major advance in the understanding of bubble structure and characteristics of bubble behaviour came with the work of Gaster4. The separation bubbles were generated by an adverse pressure gradient created by mounting an inverted airfoil over a flat plate. The separation bubbles could thus be studied on a flat plate without the effects of curvature that would have been brought about if the bubbles were generated on an airfoil. A semi-empirical model of the laminar separation bubble was developed by Horton5, using the results of Gaster and was based on the classical view of the bubble as mentioned before. Even though over the years many semi-empirical models have been proposed over the years, no major enhancement has been made on Horton’s physical description of the bubble. It should also be noted that the semi-empirical models do not represent the physics behind the structure of the bubble and its behaviour close to airfoil stall. Horton’s model describes the region of reattachment as being fully turbulent, with the fluctuations in the flow at the separation point and the laminar region being neglected. However, a presence of low frequency oscillations in low Reynolds number separation bubbles was reported by Gaster, with the fluctuations being stronger and more intermittent in long bubbles than in the short bubbles. Flow visualization studies done by Jagadeesh & Fasel6 showed the formation of well-defined vortical structures in the rear part of the laminar separation bubble, which is seen to be characteristic of the initial stages of the development of turbulent shear layer. Two-dimensional computational studies carried out by Pauley, Moin & Reynolds7, Ripley & Pauley8, Lin & Pauley9, Alam & Sandham10, Gruber et al.11, Rist et al.12, Balzer & Fasel13, 14, Hosseinverdi et al.15 provide some useful understanding of the flow physics of laminar separation bubbles. The results of the simulations show a reasonable agreement with experimental data available in the literature. It is confirmed by the numerical simulations that the separation bubble is often unsteady, with vortex...
shedding setting in at higher values of adverse pressure gradients. It is also noted that incoming disturbances have a significant effect on the stability of the separation bubble, leading to unsteadiness. Detailed numerical simulations by Balzer & Fasel and Hosseinverdi et al. reveal that the length of the separation bubble was affected by the presence of free-stream turbulence. It was also reported that in the presence of free-stream turbulence intensities ($T_u$) of up to 2%, the inviscid instability of the inflectional velocity profile in the separated flow region was responsible for the transition process. The characterization of laminar separation bubbles as being either a short bubble or a long bubble was first done by Owen & Klanfer. This was based on the length of the bubble in comparison with the chord of the airfoil on which the bubble was present. The impact of the bubbles on the overall pressure distribution over the airfoil used as a criterion by Tani to characterize the bubbles. A so-called short separation bubble on an airfoil, under certain conditions, can rapidly change into long separation bubbles. A slight change in flow conditions such as a slight increase in angle of attack, for a given flow velocity can act as a trigger for the aforementioned rapid change into a long bubble, which is also commonly known as bubble bursting. In extreme cases this bubble bursting on an airfoil could be momentary in the case of long bubble formation or an absolute breakdown as in the case of leading edge stall. For a separation bubble generated on a flat-plate by an externally imposed adverse pressure gradient, the flow will reattach eventually even in the case of a long bubble. Bubble bursting can thus be defined as the transition from one type (short bubble) to the other (long bubble), triggered by a slight change in the relevant parameters. This transition can be seen to be either gradual or rapid depending on the boundary conditions. Several semi-empirical models have been proposed over the years to predict the onset of bubble bursting, starting with the work of Owen & Klanfer. They proposed a one-parameter bursting criterion based on the local momentum thickness Reynolds number at the separation point, $Re_{\theta S}$. They indicated that the bubble bursting would occur when $Re_{\theta S} < 125$. An additional parameter based on the pressure rise over the bubble, given as

$$I = \frac{(I_{PRESSURE} + I_{PRESSURE^2})}{I_{PRESSURE}}$$

was proposed by Crabtree. Bubble bursting would occur when the pressure parameter is $\sigma > 0.35$ and $Re_{\theta S} < 125$. The bursting criterion proposed by Gaster relates the momentum-thickness Reynolds number at the location of separation (when the bubble is not present), $Re_{\theta S}$ and a non-dimensional pressure gradient parameter $P$,

$$I = \frac{I}{I_{PRESSURE}}$$

In the experimental investigation, tripping of the boundary layer provided an estimate of the inviscid pressure distribution and the velocity difference, $\Delta U$, over the length of the bubble. Based on the interpretations of Gaster’s experimental results, Horton identified the process of bubble bursting as the breakdown of the turbulent reattachment region. Furthermore, Horton identifies the onset of bursting point where the theoretical pressure recovery curve does not cross the inviscid pressure distribution. It is important to note that Horton assumed the flow to be stagnant in the laminar part of the separation bubble. This was contradicted by Schmidt & Mueller, who concluded that at low Reynolds number situations the laminar part of the bubble had a very important influence on the flow development. Diwan et al. proposed a refined bursting criterion, which takes into account not only the length of the separation bubble but also the maximum height, as it was argued that the transition to turbulence was initiated roughly at a streamwise location corresponding to the maximum height. Their refined non-dimensional pressure gradient parameter is given as

$$I^{Refined} = \frac{I}{I_{PRESSURE}}$$

where $\Delta I / \Delta I_{\theta S}$ is the actual mean velocity gradient across the bubble. The relation between the Reynolds number at the maximum height of the bubble $I^\prime$, and the refined pressure parameter $P_{Refined}$ was seen to clearly distinguish between ‘short’ and ‘long’ bubbles, thereby resulting in a single parameter criterion that indicates the transition between them. Even though several criteria exist for the prediction of bubble bursting, none have found general acceptance so far. In the present work, the concept of bubble bursting will be investigated in terms of bubble structure and dynamics. Furthermore, an attempt is made at offering a physical explanation for the bubble bursting process.
II. Experimental Setup

All experiments were conducted in the open surface water tunnel in the Hydrodynamics Laboratory of the University of Arizona. The test-section dimensions were 4.5m x 1.5m x 0.45m. Before the flow enters the test section, it passes through a turbulence management system consisting of a honeycomb, screens and a large contraction having a ratio of 18:1. This ensured the turbulence intensity $T_i$ to be very low. The turbulence intensity, $T_i$ was measured to be less than 0.1% at a flow velocity $U_\infty = 0.05$m/s. The test section consisted of a flat plate, having an elliptical leading edge. This was mounted at a height of 0.1m from the bottom wall of the test section. To generate the separation bubble on the flat plate a wing with a NACA 64-3-618 airfoil section was mounted, inverted, above the flat plate. The displacement effect of the airfoil produced the necessary pressure gradient required to generate a separation bubble. The wing has a span of 1.2m and a chord of 0.3m, with suction provided such that flow separation on the wing would be avoided at high angles of attack. Suction holes (0.001m diameter) were drilled on the entire span of suction side of the wing spanning from 50% to 90% of the chord length. The suction method proved to be very effective in assuring a steady laminar wake, with no affect on the structure of the laminar separation bubble. A steady pressure gradient was ensured by siphoning the water through the suction holes into a reservoir located 4m below the level of the water in the tunnel. The siphoned water was pumped back into the tunnel at a location downstream of the test section to maintain the level of the water level constant. Since the wing does not span the entire test section, two end plates were provided to avoid the formation of tip vortices. The end plates reach down to the flat plate and help maintain two-dimensionality of the flow in the separated region. The schematic of the experimental arrangement is given in figure 2.

Figure 2. Experimental arrangement showing the position of the inverted wing with respect to the flat plate.

A Particle Image Velocimetry (PIV) system was used to measure the vertical and horizontal components of velocity in the midspan plane of the tunnel test-section. The PIV system by LaVision, consisted of a double-pulsed 532nm Nd:YAG laser having an output of 120mJ/pulse. The light-sheet optics provided a laser sheet having a thickness of approximately 0.002m which was parallel to the flow. The laser sheet was introduced into the field of measurement from the downstream part of the test-section by using a mirror aligned at 45 degrees to the direction of flow. This allowed for the capturing of the dynamics of the entire separation bubble in real time. All measurements were made at the centerline of the test section. Two CCD cameras having a resolution of 1600x1200 pixels were used in parallel (side by side) to capture the flow field of the entire bubble. The laser and the cameras were mounted on a traverse system, which allowed for streamwise movement of the whole system without the need for recalibration. The laser and the CCD cameras were connected to a workstation via a synchronizer, which controlled the timing of the laser and the image acquisition/processing. Hollow glass spheres (Sphericel 110p8 with a specific gravity of 1.1g/cm$^3$) mixed in water were used as seeding material. The seeding particles had an average diameter of 10µm and appeared in images with diameter of between 3 and 5 pixels. Velocity vectors were derived from double frame pixel PIV images using an adaptive multi-pass cross-correlation algorithm starting with 64 X 64 pixels interrogation windows with window shifting and deformation, leading to 16 X 16 pixel interrogation windows with 50% overlap. This methodology was found to increase the peak value of correlation in comparison to the noise, which resulted in the reduction of the number of erroneous vectors and the need for vector interpolation to rectify them (LaVision$^{10}$).

Flow visualization with laser-induced fluorescent dye was used to ascertain the global structure of the laminar separation bubbles. A solution of 2% Rhodamine-B, a nontoxic pigment, was introduced into the flow 1m upstream of the displacement body by means of a dye-tube. The dye-tube was enclosed within a low-profile fairing to reduce the effect of its wake. Rhodamine-B, when excited with
an appropriate light source, the PIV laser in the present work, fluoresces (Merzkirch) and this scattered fluorescent light was captured by means of a digital camera fitted with an appropriate narrowband optical notch filter to selectively block the laser light, being emitted at a wavelength of 532nm. Since it was made sure that there was no ambient light in the vicinity of the experimental setup, only the scattered fluorescent light was captured by the camera. Figure 3 shows a typical example of the flow visualization images obtained using the above-mentioned technique.

Figure 3. Flow visualization of a typical laminar separation bubble showing the vortex shedding. Flow is from left to right. !t = !. !$%#/!.

III. Results

Experiments were conducted for unforced laminar separation bubbles for various flow velocities ranging from $0.017 \leq V_t \leq 0.091$. The flow velocities were measured 3 chord lengths upstream of the wing-displacement body, in order to avoid any possible effects thereof. The increment in flow velocities was kept small ($\sim 0.006$) so as to help capture the changes in dynamics of the separation bubble. Figure 4 shows a typical time averaged flow field upstream and downstream of the displacement body. The displacement body was placed at a distance of $x^* = 2.10$ downstream of the flat plate leading edge and at a height $y^* = 0.12$ above the surface of the flat plate. In order to achieve high temporal resolution, data was acquired for 600 seconds for each test case, at a rate of 2.5 frames per second.

Figure 4. Time averaged flow field upstream and downstream of the displacement body at an upstream flow velocity $V_t = 0.07$. The displacement body is located at $x^* = 1.10$ downstream of the flat plate leading edge.

In the sections to follow, results concerning the various aspects of the bubble geometry and its dynamics will be presented. The major aspects being the variation of length and height of the separation bubble with respect to change in flow velocity, the unsteady nature of the bubble and finally some interpretations on the topic of bubble bursting.

A. Mean quantities of the separation bubble.

Two-dimensional time averaged PIV data of the velocity field containing the laminar separation bubble is shown in figure 4. All time averaged PIV data in the present work has been averaged over 1500 samples, the total acquisition time being 600 seconds. The flow field can be divided into several distinct regions. Due to the favourable pressure gradient, the laminar boundary layer is seen to persist at first, followed by a region where the boundary layer separates due to the adverse pressure gradient imposed by the inverted wing. The separated laminar region is then followed by laminar turbulent transition and finally turbulent reattachment and the eventual fully turbulent boundary layer downstream of it. In the separated region, prior to transition, clock-wise rotating vortices can be observed in the flow visualizations, the strength of which was observed to depend on various factors such as the upstream flow velocity, and the strength of the imposed adverse pressure gradient. The angle of attack of the wing was set at 5 degrees for all the experiments discussed in this paper. This
ensured that only one parameter, namely flow velocity, could be altered to influence the dynamics of the separation bubbles. Figure 5 shows the effect of flow velocity ($f_1$) on the geometry of the separation bubble. Contours of streamwise velocity ($f$) are shown for seven different representative flow velocities. It is observed that the mean separation bubble length, which is defined as the distance between the separation point and the reattachment point, changes with the flow velocity. The length is seen to increase with decreasing upstream velocity. The point of separation was observed to be fairly constant.
The upstream velocity also influences the height of the bubble, with the height becoming smaller with increasing flow velocity. Figure 6 displays the variation of bubble length and height with the free-stream velocity. The geometric data from three experimental data sets are shown. Series-1 data correspond to experiments carried out with the airfoil at an angle of attack of 0 degrees, while series 2 and 3 correspond to experiments carried out with the airfoil at an angle of attack of 5 degrees. This change in angle of attack effectively changes the imposed pressure gradient on the flat plate.

Figure 6. Variation of bubble length and height with free-stream velocity. Data from three different experimental sets are shown. Solid symbols correspond to bubble lengths and open symbols correspond to bubble heights.

Due to the challenges of pressure measurement in a water tunnel facility, the values of coefficient of pressure ($C_p$) could not be obtained. Nevertheless it is seen that larger pressure gradient imposed by the airfoil at an angle of attack of 5 degrees results in the bubble height being greater. If pressure measurements could be made, one could safely say that the height of the separated shear layer is related to the collapse of the pressure distribution due to the shape of the bubble. Diwan & Ramesh suggested that the aspect ratio of the laminar separation bubble ($H/l$) could be used to characterise the size of laminar separation bubbles. It was shown that the height of the separation bubble increases at a greater rate with a reduction in Reynolds number compared to the bubble height. In the present case, see Figure 7, it is seen that the ratio ($H/l$) is almost a constant suggesting that the bubble height and length increases at the same rate with a reduction in Reynolds number. The data points correspond to bubbles from the experimental set Series 3.
As pointed out in the introduction, bubble bursting is defined as the process by which a switch-over is observed from short bubbles to long bubbles. This switch-over is brought about by a small change in parameters such as the flow velocity, amongst others. In the present work the experiments were conducted over a large range of flow velocities, in a decreasing order. It was intended to study the effects of velocity change on the structure and dynamics of laminar separation bubbles, thereby addressing the issue of bubble bursting. Jagadeesh & Fasel and Hosseinverdi & Fasel reported that the length of the laminar separation bubbles was seen to only increase gradually with a reduction in flow velocity. This led the authors to conjecture that the observed bubbles were of the short kind and a further reduction in flow velocity could possibly lead towards conditions amenable to bubble bursting. It has been conjectured in the literature (Gaster 1967) that the transition from a short bubble state to a long bubble was steep with a sudden change in the dimensions of the laminar separation bubble. In the following section the results from the experimental set Series-3 will be discussed.

Figure 8 shows the variation in bubble length with flow velocity. It is to be noted that the velocity difference ($\Delta V$) between any two given data points is approximately $0.005 \text{m/s}$. It is seen that the length of the bubble changes gradually at higher flow velocities ($Re_l \geq 0.038$). At a flow velocity of about $Re_l \approx 0.032$, the change in the mean bubble length is observed to be dramatic. The length of the bubble changes from being about $l_{rms} = 0.4$ to about $l_{rms} = 0.55$. This corresponds to a change of 0.15, with a 35% increase in bubble length. Figure 5 shows the time-averaged streamwise velocity contours of the bubble at $Re_l \approx 0.032$. The time-averaged contours show the full extent of the laminar separation bubble. The field of view of the two-camera PIV system was about 0.5m, and this was insufficient to capture the entire length of the bubble. The cameras were then moved downstream by 0.33m to capture the dynamics at the reattachment point. The two data sets were stitched to form a composite time-averaged contour plot as seen in figure 5. It can also be observed that the reattachment point is not very well defined, compared to the cases at higher flow velocities. This is due to the fact that the
periodic activity in the rear of the bubble is of very low frequency and that the total acquisition time of 600 seconds was probably not enough to provide a reliable average. The drastic change in bubble length was ascertained as likely being due to the bubble bursting process. In order to further verify this, it was decided to analyze the bubble data in terms of the criterion for bursting as proposed by Gaster (1967), the details of which were discussed in the introduction (Equation 2). Since the bursting criterion assumes an inviscid flow field, it was necessary to obtain the velocities at the edge of the unseparated boundary layer at the separation and reattachment locations. A boundary layer trip, consisting of zig-zag tape mounted on a stainless steel rod, was placed upstream of the separation location. This ensured that the boundary layer on the flat plate would not separate. It is to be noted that the boundary layer trip as mentioned only works at higher flow velocities. At lower flow velocities, the boundary layer trip was seen to be ineffective and separation was still present.

In order to obtain data for potential (inviscid) flow conditions at low flow velocities, use was made of commercially available CFD software FLUENT to determine the inviscid flow field for experimental setup. The experimental setup was modeled by a 2-D channel flow with a slip wall condition at the flat plate and a uniform streamwise velocity at the inflow and outflow. Figure 9 shows the setup used for the CFD calculations along with the contours of streamwise velocity at a free-stream velocity $U_0 = 0.047$. The flow is seen to accelerate as it approaches the displacement body and since the calculation was inviscid, the flow does not separate and hence the separation bubble is absent. Figure 10 shows the variation of $CI^*$ with the non-dimensional pressure parameter $P$. Also plotted is the Thwaites separation criterion (Thwaites23), Owen’s bursting criterion (Owen & Klanfer) and the bursting line as proposed by Gaster. It can be noted here that the data points from the present experiments do not cross the bursting line, even though the trend appears to follow the bursting line. The value of $CI^*$ for the case where a drastic change in bubble length was observed is seen to coincide with Owen’s bursting criterion, the value of which is given as $CI^* = 125$. 

![Figure 8. Variation of bubble length with free-stream velocity. Data from experimental set Series-3.](image)

![Figure 9. Setup used for the inviscid CFD calculations using FLUENT. Results show contours of streamwise velocity at a free-stream velocity $U_0 = 0.047$.](image)
Figure 10. Variation of $!"'$ with the non-dimensional pressure parameter $P$. Data from experimental set Series-3.

Even though the data points don't actually reach the bursting line, the general trend makes sense, as it is quite evident that bursting is more likely to occur for low values of $!"'$ or for high values of negative $P$. This trend of $P$ lying above the bursting line make the argument of bubble bursting in the present work inconclusive, based on the Gaster’s bursting criterion. It is seen from the literature that values of $P$ and $!"'$ need to be determined accurately. Even though $!"'$ is not strongly dependent on the incoming disturbance, the values of $P$ are. This is made more difficult in the present work due to the lack of pressure data. Hosseinverdi & Fasel’s\textsuperscript{22} complementary DNS investigations are crucial in this endeavour as the results obtained therein could shed more light on the effect of the incoming disturbances on the dynamics of bubble bursting.

B. Unsteady characteristics of the separation bubble.

Since the process of bursting is seen to be a dynamic one (Marxen & Henningson\textsuperscript{24}) it is important to characterise the unsteady nature of the separation bubbles. The sudden change that was observed in the time-averaged bubble geometry suggests that it could be on the verge of bursting or already burst. The time-resolved PIV results of the flow in the separation bubble before and after the sudden change in average length will be presented here. Flow visualization was used as a qualitative tool to study the structure of the bubbles. Figure 11 shows the difference in the instantaneous structure of the separation bubbles at two different flow velocities. These represent the two extreme cases in the present study, at very high and low flow velocities, $!t_1 = 0.091 \text{ m/s}$ and $!t_1 = 0.028 \text{ m/s}$. The structure of the laminar separation bubbles and the unsteady nature of the reattachment region are apparent from the flow visualization images. The qualitative difference in the development and shedding of vortical structures at the two given free-stream velocities is also elucidated. It is also evident from the flow visualization that the separation point moves downstream at higher flow velocities.

Figure 11. Flow visualization showing the structure of the laminar separation bubble at a flow velocity of $!t_1 = 0.091 \text{ m/s}$ and $!t_1 = 0.028 \text{ m/s}$.
The presence of unsteady structures in the downstream part of the separation bubbles at even very low flow velocities (lower than the flow velocity at which the length change was observed) is contrary to the results obtained by Pauley et al., who report a steady separation bubble at low flow velocities. This is due to the fact that in the simulations of Pauley et al. the effect of free-stream turbulence was not included, which is contrary to experimental conditions where one can expect a finite value of free-stream turbulence to be present.

Figure 12. Instantaneous spanwise vorticity contours at a flow velocity $U = \text{constant}$ showing the evolution of vortices. The time between the frames $\Delta t = \text{constant}$ seconds.

Figure 13. Instantaneous spanwise vorticity contours at a flow velocity $U = \text{constant}$ showing (1) the vortex shedding process and (2) the low frequency flapping motion. The time between the frames $\Delta t = \text{constant}$ seconds.
Instantaneous flow fields, obtained by PIV, of the laminar separation bubble are shown in figure 12 and figure 13. While figure 12 shows the spatio-temporal reconstruction of the contours of spanwise vorticity at a free-stream velocity of \( \hat{U}_1 = 0.053 \frac{\text{m}}{\text{s}} \), figure 13 (1) and (2) show the spanwise vorticity contours at a free-stream velocity \( \hat{U}_1 = 0.032 \frac{\text{m}}{\text{s}} \) at two different stages of its vortex shedding process. The development of vortices is clearly observed in both the cases. The time interval between the snapshots for the case presented in figure 12 is 0.8 seconds. Here the onset of transition takes place at a streamwise distance of approximately 2.5m downstream of the flat plate leading edge. The shear layer roll-up starts as a small disturbance upstream of the transition location. With increasing time, the disturbance grows until a large vortex is formed (figure 12(b)). The vortex travels downstream at a velocity equal to about 60% that of the local free-stream velocity. The vortex travels downstream until it is shed from the shear layer of the separation bubble. Visual inspection of the distances between the vortices in figure 12 shows a periodicity in vortex development. Downstream of the laminar separation bubble, large-scale structures are seen to break down, which leads to a turbulent boundary layer. This process of vortex shedding was observed at all the flow velocities that were investigated in the present work. Figure 13(1) shows the vortex shedding process at a much lower flow velocity, corresponding to the case where the abrupt change in the mean bubble length was observed. The time period of vortex shedding is observed to be much larger in this case, taking at least 10 seconds between each vortex shedding cycle. It was also noted that the vortex shedding process was not regular, with the separation bubble ceasing to shed vortices at times. One such instance is shown in figure 13(2). The time between frames is the same as that in figure 13(1), 2.4 seconds. During this period of relative inactivity, a low frequency flapping motion of the separated shear layer in the rear of the bubble was observed. During flow visualization studies, the frequency of this activity was estimated to be roughly of the order of 0.001Hz. It is conjectured that low frequency, long wave length disturbances typically of the size of the laminar separation bubble may lead to the bubble itself to act as a resonator and that for large bubbles it is possible that this mechanism is responsible for the low frequency oscillation of the separating shear layer (Hammond & Redekopp\(^25\), Boiko \textit{et al.}\(^26\)). The time series plots of velocity fluctuation in the shear layer of the bubbles for five different flow velocities are shown in figure 14. Each peak corresponds to the passing of a flow structure. It is evident that the free-stream velocity has a strong influence on the natural shedding frequency of a laminar separation bubble.

![Figure 14. Time history of velocity fluctuations at five different flow velocities and corresponding frequency spectra for two relevant cases. The spectra are shifted in amplitude for clarity.](image)

Figure 14 shows the frequency spectrum of the velocity fluctuations at two flow velocities \( \hat{U}_1 = 0.032 \frac{\text{m}}{\text{s}} \) and \( \hat{U}_1 = 0.053 \frac{\text{m}}{\text{s}} \). The spectrum shows a dominant peak corresponding to the natural shedding frequency. The presence of low frequency activity in the lower flow velocity case was discussed earlier. In the corresponding spectrum one can detect the frequency of vortex shedding to be around 0.1Hz. The low frequency activity is not represented in the spectrum due to the fact that the acquisition time was not long enough; even though data was collected for 600 seconds. One can broadly divide the natural fluctuations in the separated shear layer of the bubble into low frequency and high frequency oscillations. In the spectrum corresponding to the higher free-stream velocity, the dominant high frequencies range from about 0.25Hz to 1.25Hz and the low frequencies are less than 0.25Hz. The origin and role of the low frequency component is not yet fully understood and will be investigated in our group in future. This topic has also been addressed in the literature (Haggmark \textit{et al.}\(^27\)) and it may be due to a global instability. Such a low frequency component was also observed in
separation bubbles caused by shock wave-boundary-layer interactions by Dussauge et al.\textsuperscript{28}. They reported that the structure of the separation bubble was at the origin of the unsteadiness, with the fluctuation frequencies being much lower than the characteristic frequencies of turbulence in the free-stream boundary layer.

IV. Conclusions

A two dimensional laminar separation bubble was studied experimentally in a water tunnel. The separation bubble was induced on a flat plate by an adverse pressure gradient, which was generated by an inverted wing mounted above the flat plate. The present experiments use a combination of flow visualization and PIV measurements to provide an insight into the dynamics of laminar separation bubbles for different flow conditions. Particular emphasis of this work is on understanding the phenomenon of “bubble bursting”. Towards this end, the variation of bubble geometry and dynamics were studied for a range of flow velocities, in order to find the conditions where the geometry of the bubble underwent a sudden change when the flow velocity was reduced below a certain value. The length and height of the separation bubbles increased with a reduction in free-stream velocity. It was noted that at a free-stream velocity $U_f = 0.032 U_\infty$ the length of the bubble changed drastically. This corresponds to a Reynolds number based on the momentum thickness at separation $Re = 125$, which coincides with Owen’s bursting criterion. The possibility of classifying this change as being the process of bubble-bursting in the present experiments was made. Even though the data from the present experiment do not cross the bursting line as proposed by Gaster, their trend appears to follow it. Spatiotemporal analysis of the PIV data and flow visualization studies revealed the presence of a very low frequency activity of the separated shear for the lowest flow velocity case. The frequency of this activity was estimated to be of the order of 0.001Hz, by means of flow visualization studies. Further investigation into the origin and its role in the process of bubble bursting process is under investigation by our research group.

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References


