Development of Laminar Boundary Layers

The preceding sections detailing the analytical solutions for the flows in laminar boundary layers allow an understanding of how the boundary layer develops as a high Reynolds number external flow progresses around an object. Immediately following the front stagnation point, the velocity outside the layer increases linearly with distance from that point. The corresponding $m = 1$ Falkner-Skan solution indicates that the boundary layer thickness remains relatively constant during this initial phase but as the acceleration decreases and m falls below one, the thickness will begin to grow and that growth increases as dU/ds and m decrease. During this acceleration phase the velocity profile in the boundary layer remains quite blunt with large $\partial u/\partial n$ velocity gradients and correspondingly large surface shear stresses.

A critical point occurs when the acceleration ceases at the point on the surface where the pressure reaches its minimum value and velocity reaches its maximum. This corresponds to the $m = 0$ Falkner-Skan solution (or the Blasius solution); the velocity profile is still quite blunt with a moderate velocity gradient, $\partial u/\partial n$, and the surface shear stress is still positive. However, downstream of this minimum pressure point the flow begins to decelerate with negative m values. Two important developments are possible in this post-minimum pressure region and the subsequent evolution of the flow is very dependent on (1) whether or not these developments occur and (2) which of them occurs first.

Those two possible game-changing developments are:

- Instability of the flow in the boundary layer leading to transition from laminar to turbulent flow in the boundary layer. Instability first occurs when the velocity profile develops an inflection point and, in the Falkner-Skan family, this corresponds to $m = -0.0654$ as shown in the second figure in section (Bje). We delay detailed discussion of the mechanism of instability and the subsequent transition to turbulence until the general topics of instability and turbulence are addressed in sections (Bk). However it is important in the present context to take note of the fact that both the location where the layer first becomes unstable and the point at which the layer starts transition to turbulence are important to identify.

- The laminar boundary layer separates from the surface. This separation point occurs when the velocity gradient, $\partial u/\partial n$, and the surface shear stress reach zero. The profile at this point corresponds to the Falkner-Skan solution with $m = -0.0904$ (see the second figure in section (Bje)) as indicated by profile C in Figure 1. It is important to note that the separation point can be identified as the location where the shear stress drops to zero and various flow visualization techniques make use of this feature in an effort to identify the separation point experimentally. Downstream of the separation point m falls below the critical value of -0.0904 and the velocity profile develops a layer of reverse flow next to the solid surface. As sketched in Figure 1, the flow downstream of the separation point necessarily involves a region of flow recirculation in which flow next the solid surface progresses upstream and then is turned by the approaching flow to join the downstream flow further from the surface.

Both the potential turbulent transition location and the potential separation point are very important to determine in any prediction of the progress of the flow downstream of the minimum pressure point. If transition to turbulence occurs first the turbulent boundary layer may remain unseparated until much further downstream. On the other hand if separation occurs first, transition will normally follow on the downstream separation streamline. Then two scenarios are possible. In the first the transitioning *free shear layer* progresses downstream, defines the outer envelope of the wake and determines the state of the flow in the wake between the free shear layers. The other scenario occurs when the transition on the free shear layer occurs close to the solid surface and the turbulent boundary layer *reattaches* to that surface. The turbulent boundary layer thus created often remains attached for a significant distance downstream. In this latter case the short *laminar separation "bubble"* is a feature that often occurs, for example, near the leading edge of an airfoil and is an often overlooked feature. Examples of these features will be discussed in the sections on the lift and drag produced in external flows.

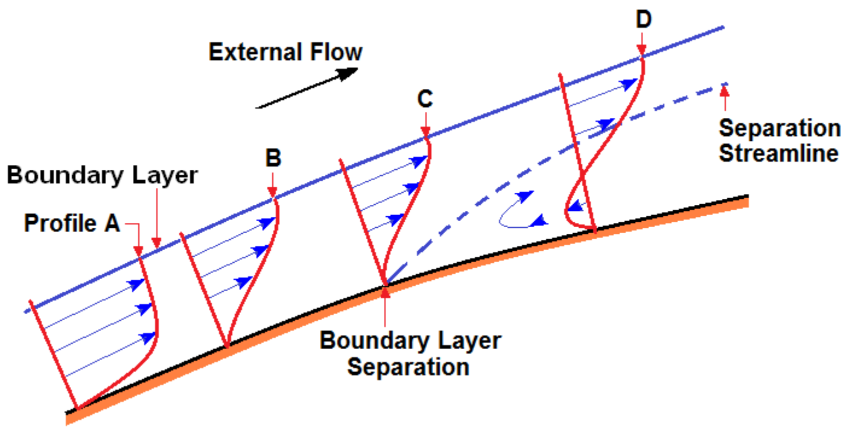

Figure 1: Sketch demonstrating the development of a laminar boundary layer in a decelerating external flow.

Figure 2 is a shadowgraph photograph visualizing the developments in the flow near the surface of an object in a water tunnel. It demonstrates how complex the boundary layer development can be. The flow is from the right to the left. The entering flow on the right is a laminar boundary layer visualized by a thin white layer next to the object surface. Laminar boundary layer separation then takes place as indicated and, after a brief pause, instability occurs leading to waves and the beginning of transition to turbulence. This unsteady flow reattaches to the object surface and transition continues leading to an attached turbulent boundary layer that leaves the left side of the frame.

However separation comes about, whether laminar or turbulent, it initiates the wake behind an object and therefore can cause a major conformational change in the geometry of that flow. The wake, in turn, leads to a major change in the drag on the object as described in section (Dbc). Hence the ability to predict and, perhaps, control separation is very important for any effort to understand the drag on an object in a flow. A question that puzzled many of the early fluid mechanics scholars was how could viscosity make any difference in a high Reynolds number flow for which the viscous terms in the equations of motion are

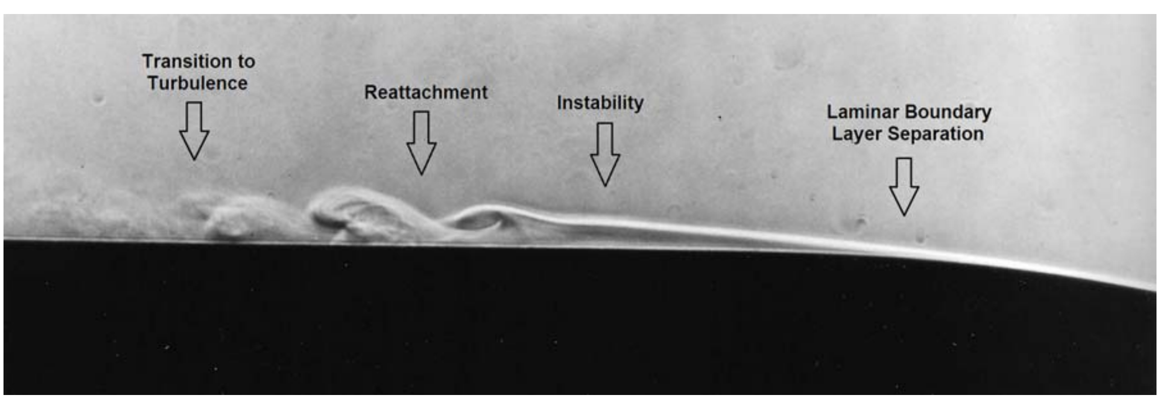

Figure 2: Shadowgraph photograph taken by V. Arakeri of the development of the boundary layer flow on the surface of an object in a water tunnel. The flow is from the right to the left.

demonstrably small compared with the inertial terms? The answer is that the viscous terms are very small compared with the inertial terms almost everywhere *except close to the solid surface where the inertial terms tend to zero.* And this, in turn, can lead to boundary layer separation and a major change in the flow. We illustrate these changes in later sections on the lift and drag on bodies in flows.