Aerodynamics

Airfoils

Viscous effects

- A real fluid has viscosity and so the flow must satisfy the no slip condition. This means that flow (and forces) obtained for an ideal fluid are not identical to those observed in the real flow.

YouTube - how wings work? Smoke streamlines around an airfoil
YouTube - Fluid Mechanics – airfoil
YouTube - Airfoil Stall (I)
Aerodynamics

Airfoils
Viscous effects

• At small angles of attack, the boundary-layers that develop on the upper and lower surfaces of the airfoil do not separate and so we have a thin wake (viscous region)

• The increase of the angle of attack leads to flow separation and so we have a wake (viscous region) of large dimension that leads to the decrease of lift (stall)
Aerodynamics

Airfoils

Viscous effects

• The lift, $C_l$, and drag, $C_d$, coefficients obtained experimentally do not match the results obtained for an ideal fluid

• Drag force has two components: friction due to the shear-stress at the wall; pressure resistance originated by the displacement imposed by the viscous region to the outer flow streamlines
Aerodynamics

Airfoils

Viscous effects

• At small angles of attack, the pressure distribution for a real fluid is slightly different from that predicted for an ideal fluid (δ* effect)

• The differences depend on the angle of attack (pressure gradients) and on the Reynolds number

\[ R_e = \frac{|\vec{V}_\infty| c}{\nu} \]
Aerodynamics

Airfoils
Viscous effects

• Qualitatively, the effect of viscosity may be analysed with an ideal fluid approach that includes the displacement of the streamlines imposed by the boundary-layers and wake of the airfoil (viscous region)

• The displacement thickness, $\delta^*$, depends on the pressure gradient. An adverse pressure gradient leads to a larger increase of $\delta^*$ than a favourable pressure gradient
Aerodynamics

Airfoils
Viscous effects

• Transition to turbulent flow is favoured by adverse pressure gradients. In turbulent flow, the boundary-layer grows significantly more than in laminar regime (about 6 times more for a zero pressure gradient)
Aerodynamics

Airfoils

Viscous effects

• The differences between the pressure distributions obtained for a real and an ideal fluid are a consequence of the reduction of the streamline curvature imposed by the behaviour of the displacement thickness of the viscous region.
Aerodynamics

Airfoils
Viscous effects

• The effect of viscosity in $C_l$ may be interpreted as a reduction of the angle of attack that leads to a decrease of the lift coefficient, $C_l$. At small angles of attack (in the absence of flow separation), the effect is gradual and so $C_l$ remains approximately a linear function of $\alpha$. 
Aerodynamics

**Airfoils**

**Viscous effects**

- The viscosity originates a resistance force that is a consequence of the shear-stress at the wall, $\tau_w$

- The “equivalent body” (geometry+$\delta^*$) for an ideal fluid analysis becomes semi-infinite. This means that the integration of the surface pressure distribution introduces a pressure resistance component.
Aerodynamics

Airfoils

Viscous effects

Conventional airfoils

Masters of Mechanical Engineering
Aerodynamics

Airfoils

Viscous effects

Laminar airfoils
Aerodynamics

Airfoils

Laminar airfoils

Viscous effects

- Favourable or zero pressure gradient delays transition to turbulent flow. Shear-stress at the wall is smaller in laminar flow than in turbulent flow causing a reduction of friction resistance. Smallest increase of the boundary-layer in laminar regime also reduces the displacement thickness and consequently the pressure resistance.
Aerodynamics

Airfoils

Viscous effects

Laminar airfoils

- Range of angles of attack without suction peak is practically coincident with the “laminar bucket” observed in the curve that represents drag as a function of lift (polar $C_l$, $C_d$)
Aerodynamics

Airfoils
Viscous effects

• The increase of the angle of attack originates adverse pressure gradients that may lead to flow separation. In such conditions, the real flow is significantly different from that obtained theoretically for an ideal fluid.
Aerodynamics

Airfoils

Viscous effects

- Significant regions of separated flow lead to a decrease of the lift force (stall) and a significant increase of the pressure resistance force (pressure component of drag). The occurrence of flow separation is related to the pressure distribution, i.e. the shape of the airfoil
Aerodynamics

Airfoils
Viscous effects

• At “large” angles of attack, thin airfoils exhibit severe adverse pressure gradients close to the leading edge. Separation appear close to the leading edge and the length of the separation bubble grows with the increase of the angle of attack.

• This is a smooth type of stall typical of thin airfoils, designated by “thin airfoils stall”
Aerodynamics

Airfoils

Viscous effects

\(d/c = 3\%, \ \alpha = 3^\circ\)
Aerodynamics

Airfoils

Viscous effects

Development of stall for a flat plate
Aerodynamics

Airfoils
Viscous effects

• At “large” angles of attack, thick airfoils lead to mild adverse pressure gradients that cover the complete upper ($\alpha>0$) surface. Separation appears close to the trailing edge and separation point moves upstream with the increase of the angle of attack.

• This is a smooth type of stall typical of thick airfoils, designated by “trailing edge stall”.
Aerodynamics

Airfoils
Viscous effects

• At “large” angles of attack, airfoils with around 9% relative thickness may exhibit a small separation bubble at the leading edge (laminar separation, transition to turbulent and re-attachment by Coanda effect) with a typical length of 1% of the chord. At a given angle of attack, the bubble “bursts” originating a massively separated flow

• This is a sudden type of stall designated by “leading edge stall”
Aerodynamics

Airfoils
Viscous effects

Trailing edge stall – 633-018
Leading edge stall – 63-009, 631-012
Thin airfoil stall – 64A006

Masters of Mechanical Engineering
Aerodynamics

Airfoils
Viscous effects

- The circulation required to satisfy Kutta’s condition is a consequence of the vorticity of the viscous flow region close to the airfoil surface.

- It is always possible to define a contour sufficiently far from the airfoil to have negligible viscous effects. Therefore, the total circulation of any flow started from rest must remain equal to zero.
Aerodynamics

Airfoils
Viscous effects

• The “circulation conservation” is guaranteed by the starting vortex
  - For low velocities $R_e \rightarrow 0$ and so the streamlines are similar to those obtained for an ideal fluid
  - A flow separation region appears at the trailing edge that is only stable for very small Reynolds numbers
  - The starting vortex is convected by the flow and leaves a circulation of opposite sign around the airfoil guaranteeing that the total circulation remains equal to zero
Aerodynamics

Airfoils

Viscous effects

a) Flow immediately after the start
b) Formation of the starting vortex
c) Release of the starting vortex
d) Equivalent to c) but with camera fixed relatively to the fluid

Masters of Mechanical Engineering
Aerodynamics

Airfoils
Viscous effects

Starting and stopping vortices

Masters of Mechanical Engineering