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Aerodynamics and Numerical Simulation Methods

Realistic Boundary Layers

University of BRISTOL

Today

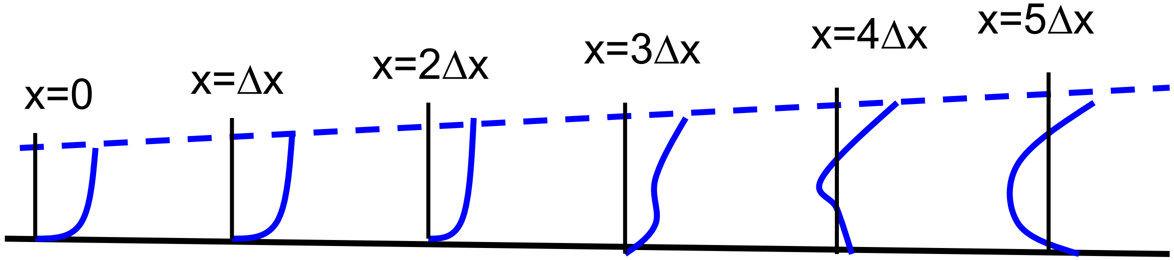
- Separation
- Shock-boundary layer interaction
- Laminar aerofoils and boundary layer suction
- Lift enhancement by blowing

Separation

- So far in the course we have only considered boundary layers which experience relatively mild external gradients, or in the case of a flat plate, no gradients at all.
  - results in thin, attached boundary layers
  - true for most of the flow over streamlined bodies at small incidence
- However, not true all the time

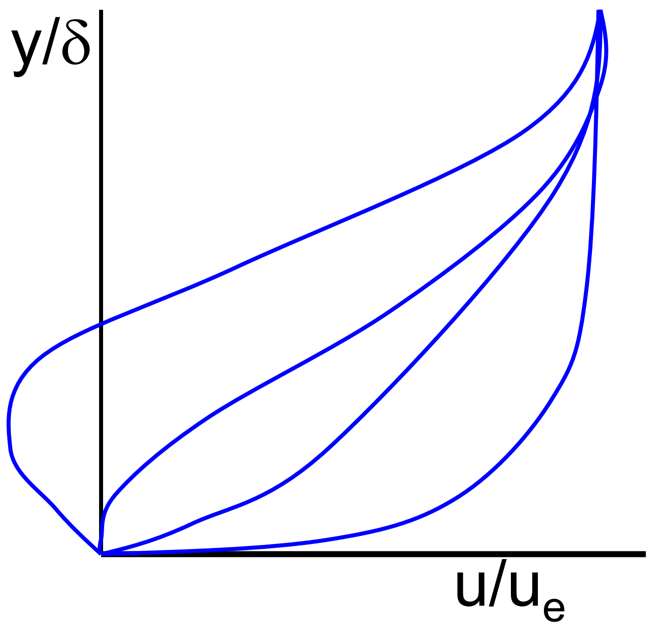
Separation

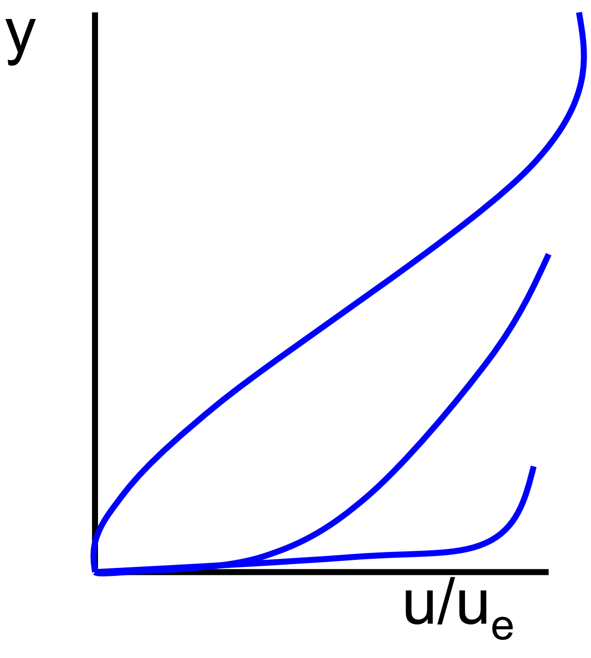
- Adverse pressure gradient (i.e. $\dfrac{dP}{dx} > 0, \rightarrow \dfrac{dU_e}{dx} < 0$)
- Occurs over rear part of most vehicles
  - in generating lift, air is accelerated
  - flow must therefore slow down towards rear stagnation region
- Some of the kinetic energy of the flow must turn to pressure (i.e. potential energy) to get through the adverse gradient, causes velocity profile to change:



Leads to

- Greater growth of boundary layer, hence higher drag
- Change in b.l. thickness δ due to change in velocity profile



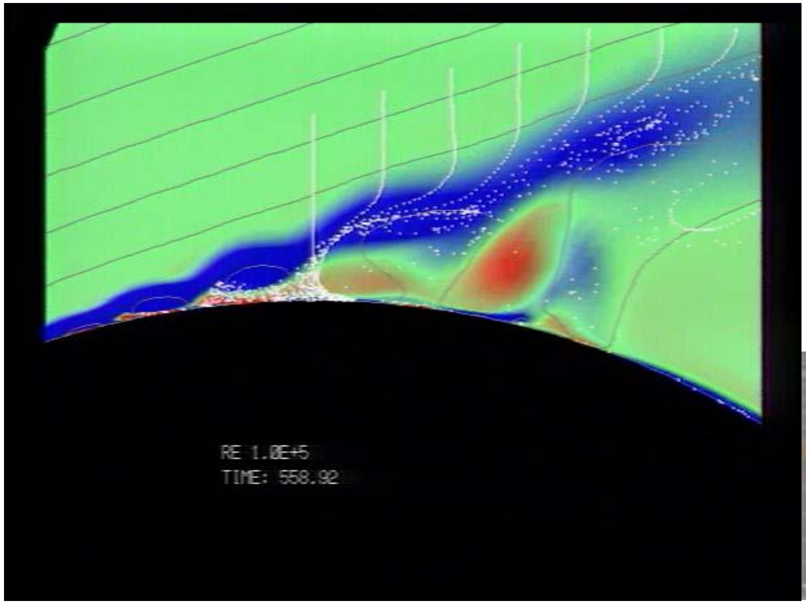


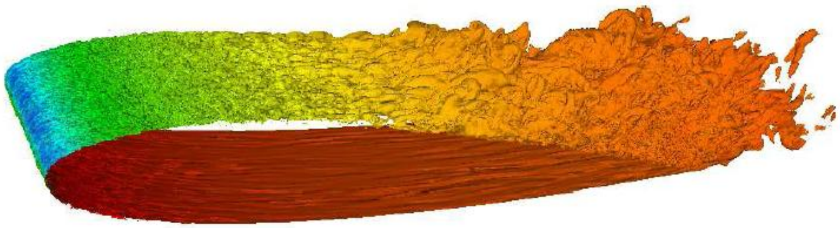
Results in

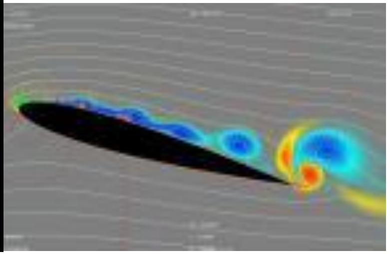
- zero skin friction at separation
- reversed flows, and changes in flow behaviour
  - unsteady
  - three dimensional
  - dimensions significant w.r.t. body
- Therefore, violates most of the assumptions we have made in this course thus far – methods described cannot be used for any significant separation

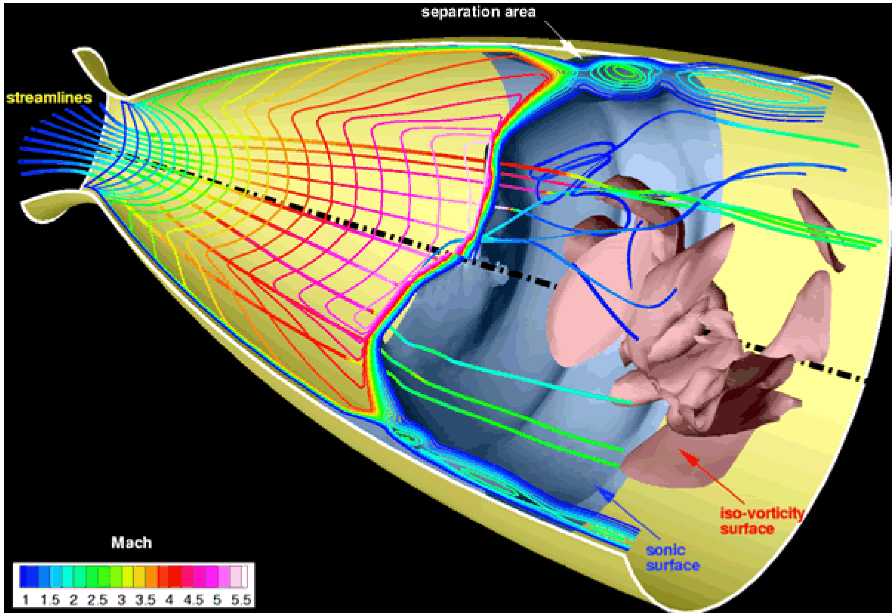
Location of separation

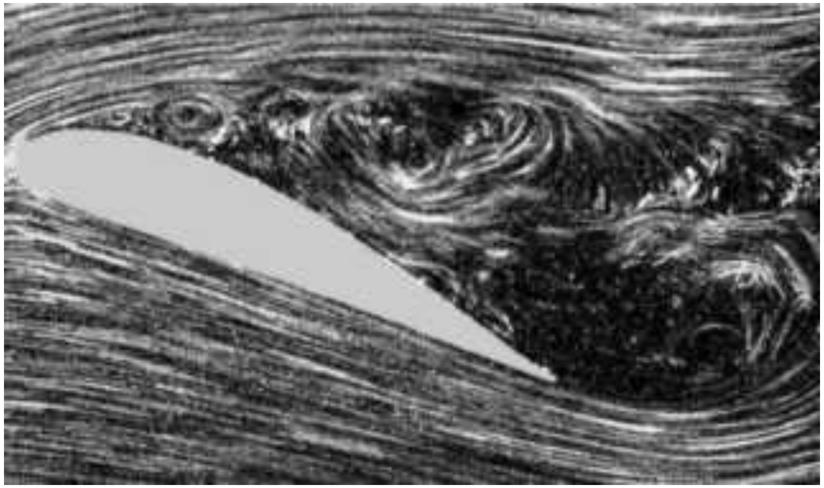
- Location can be very difficult to predict
- depends on pressure gradient, plus
  - geometry
  - laminar/turbulent
  - shock wave interaction
  - turbulence in main flow
  - 3D effects (i.e. gradients in other directions)
- Can try to predict using NS solutions + turb model, but results should be viewed with caution


RE 1.0E+5
TIME: 558.92





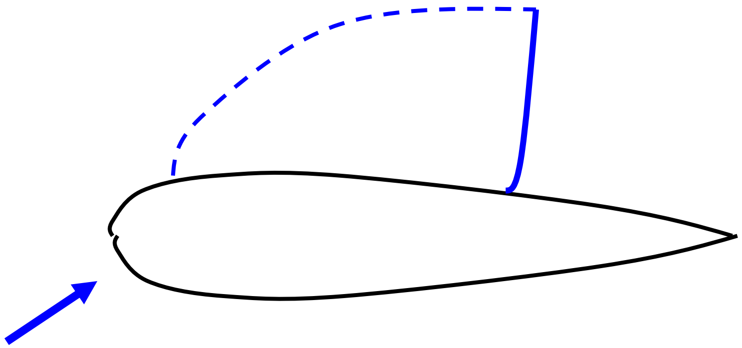

separation area
streamlines
iso-vorticity surface
sonic surface
Mach
1 1.5 2 2.5 3 3.5 4 4.5 5 5.5

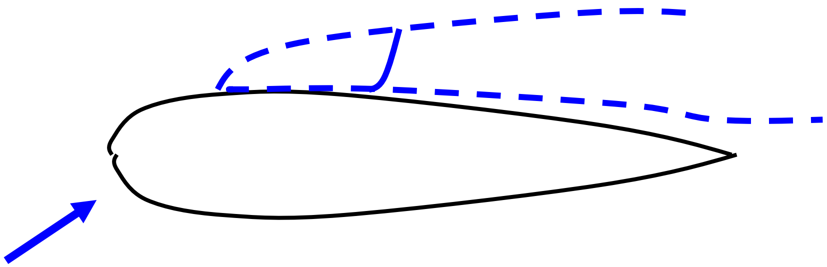


Shock interactions

- Obviously only occurs in supersonic flows, or flows with regions of supersonic flow, e.g.
  - flow over wings of aircraft in transonic flows
  - supersonic vehicles
  - rocket and jet exhausts
- Boundary layer allows communication of presence of the shock wave upstream at the wall.
- Adverse gradient causes thickening of boundary layer, and influences main flow:

On a transonic aerofoil

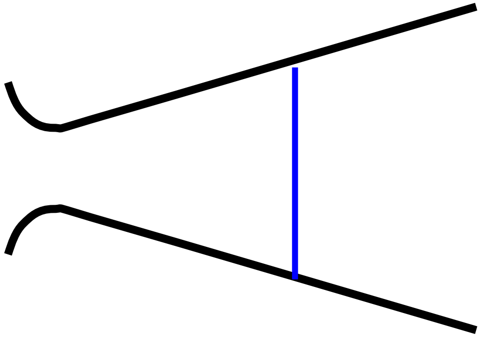


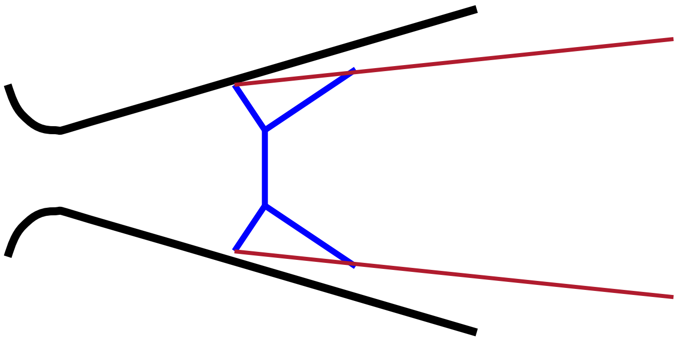


Inviscid

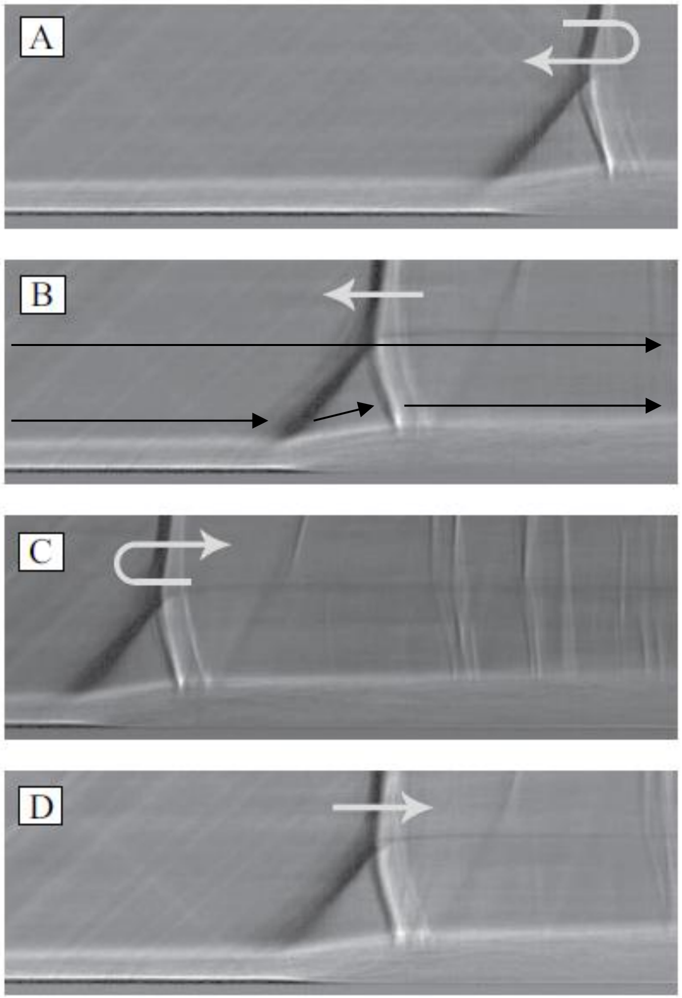
Viscous

In a nozzle

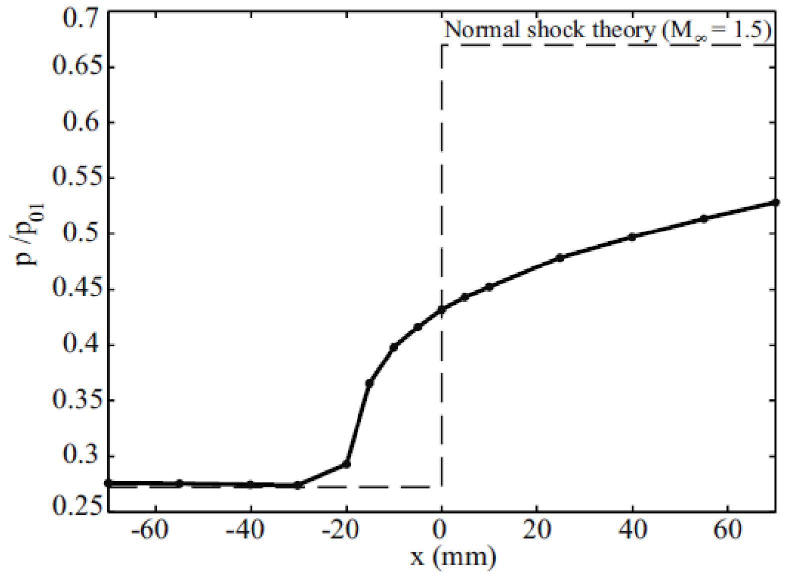


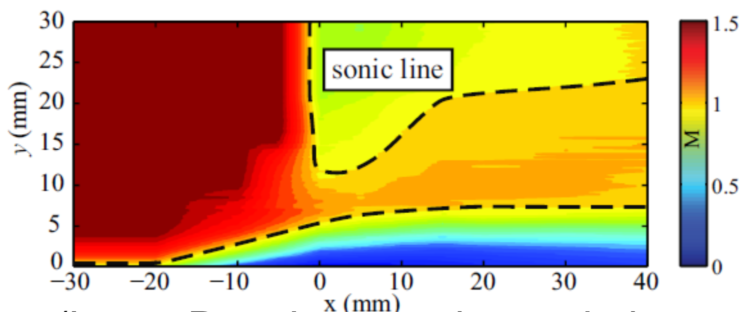


Normal shock-boundary layer interaction



(measured at wall)

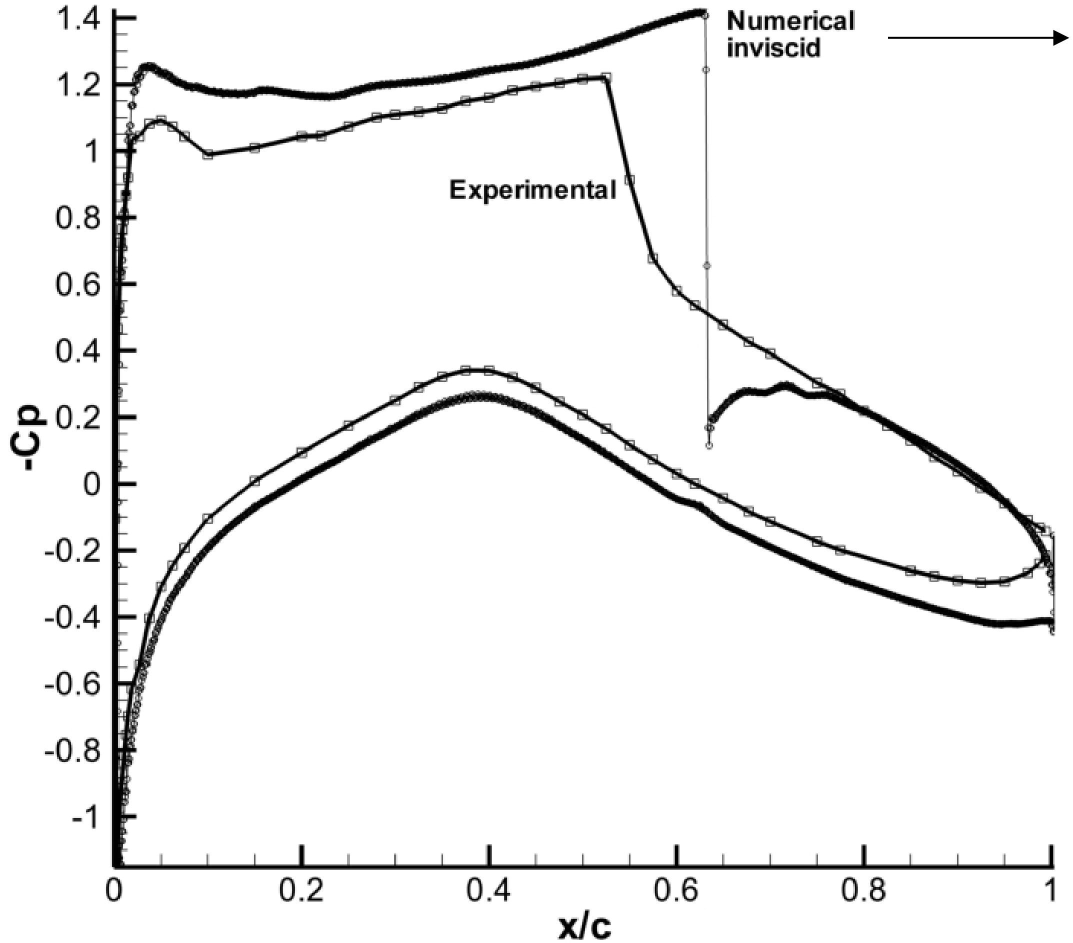


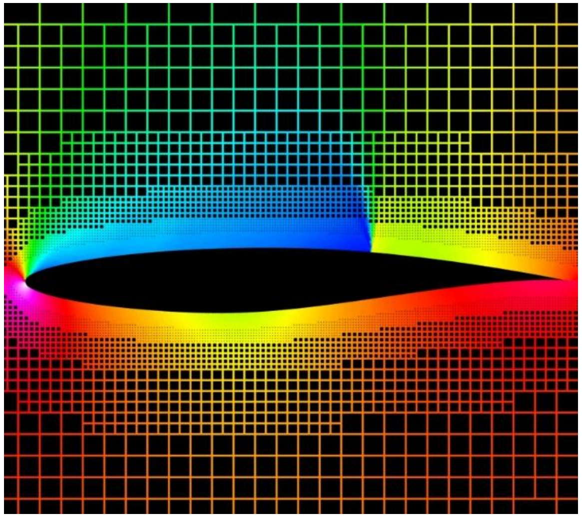


(Laser Doppler experimental picture of

Mach number)

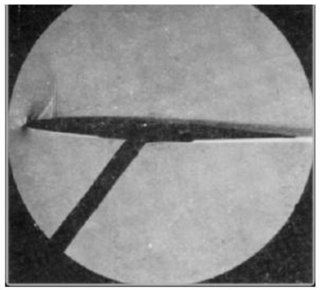
Cp comparison RAE 2822, M=0.729, 2.31deg



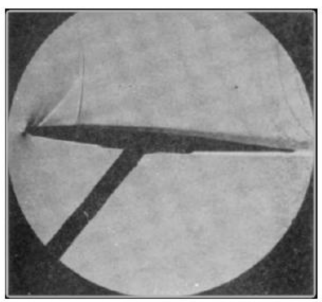


Shock induced separation

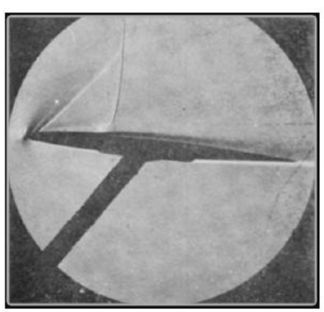
M=0.75, 6% thick



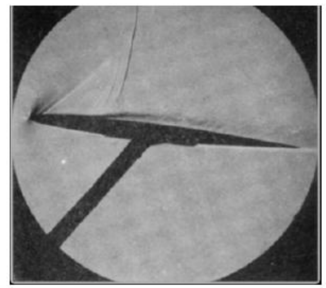
a. α = 2.7 deg



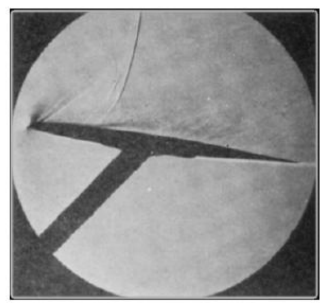
b. α = 3.7 deg



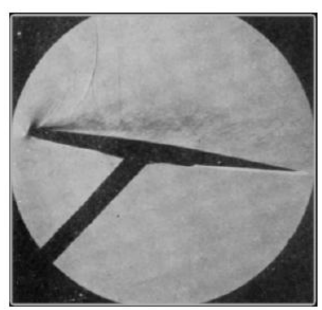
e. α = 4.7 deg



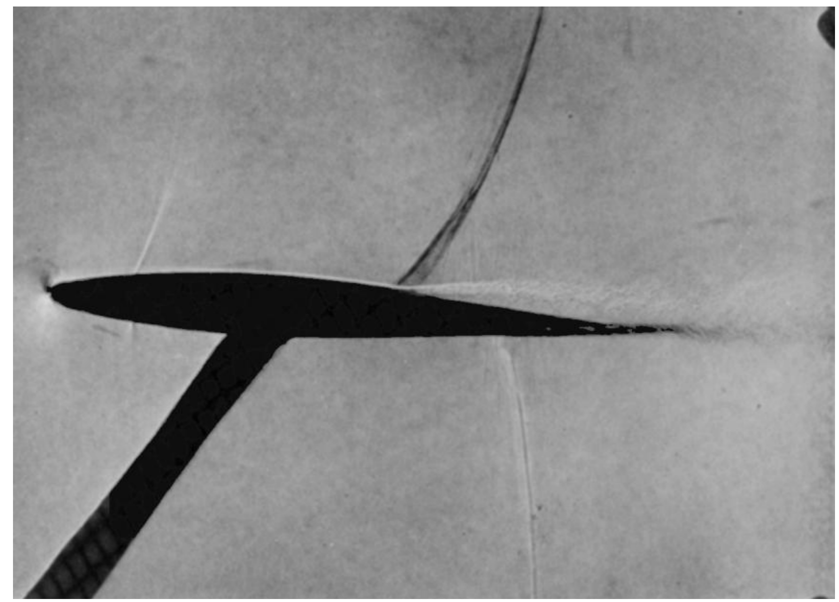
d. α = 5.7 deg



e. α = 6.7 deg



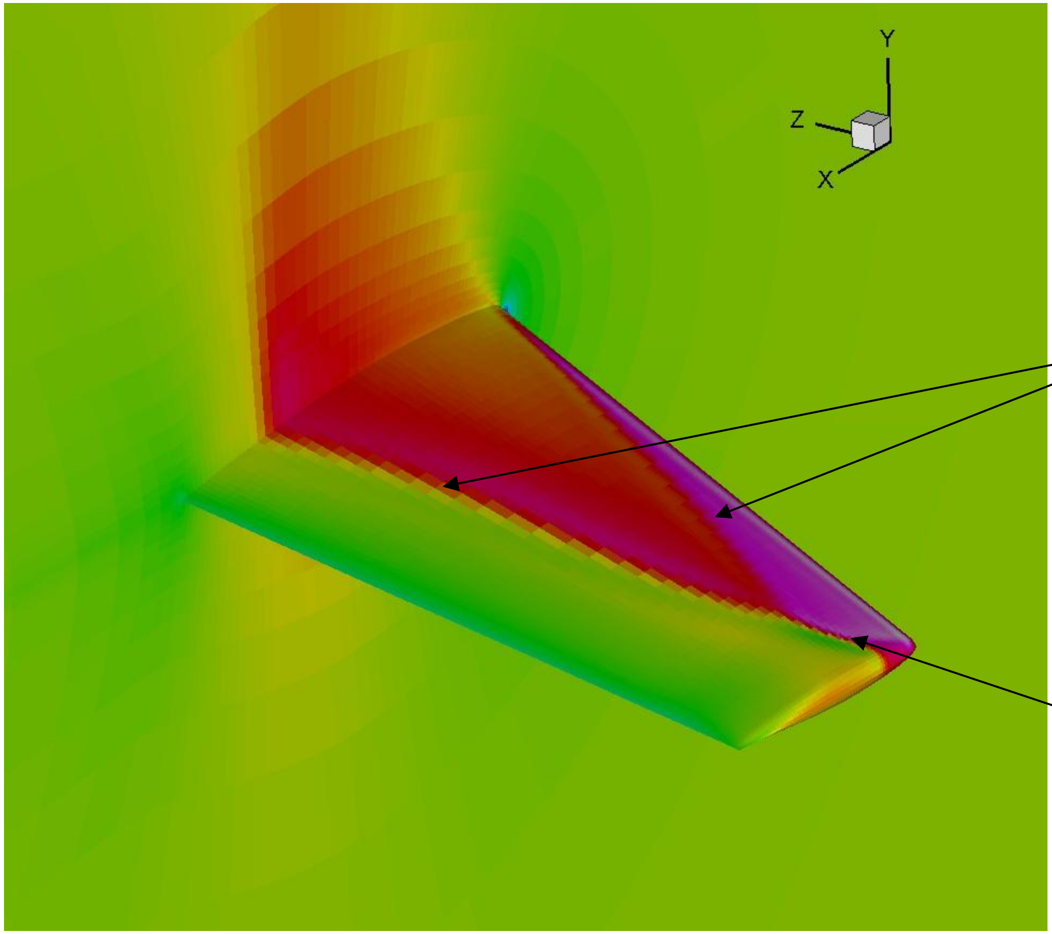
f. α = 7.7 deg



M=0.88, AoA=2deg, 10% thick

3D inviscid

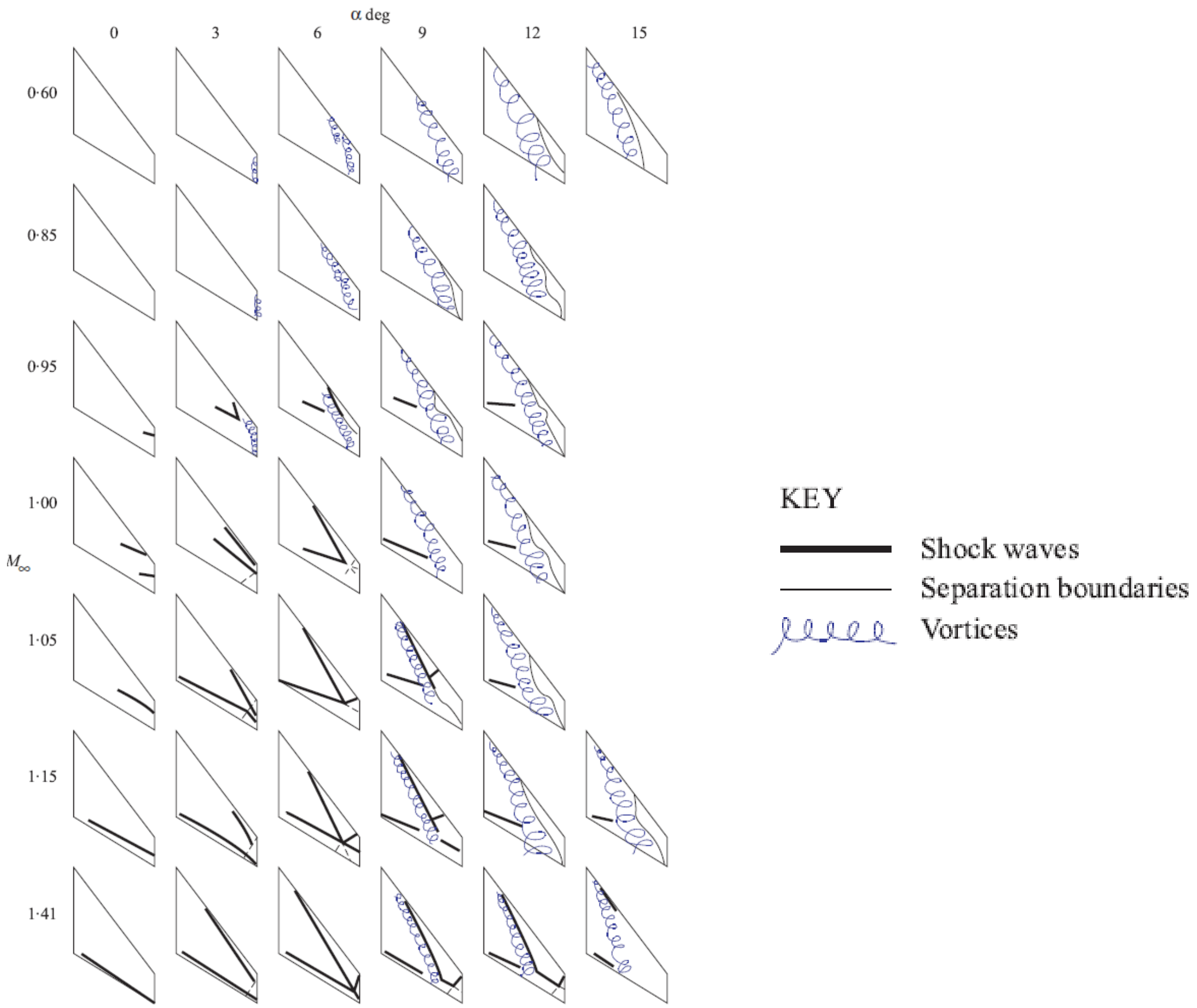
SBLI even more complicated in 3D



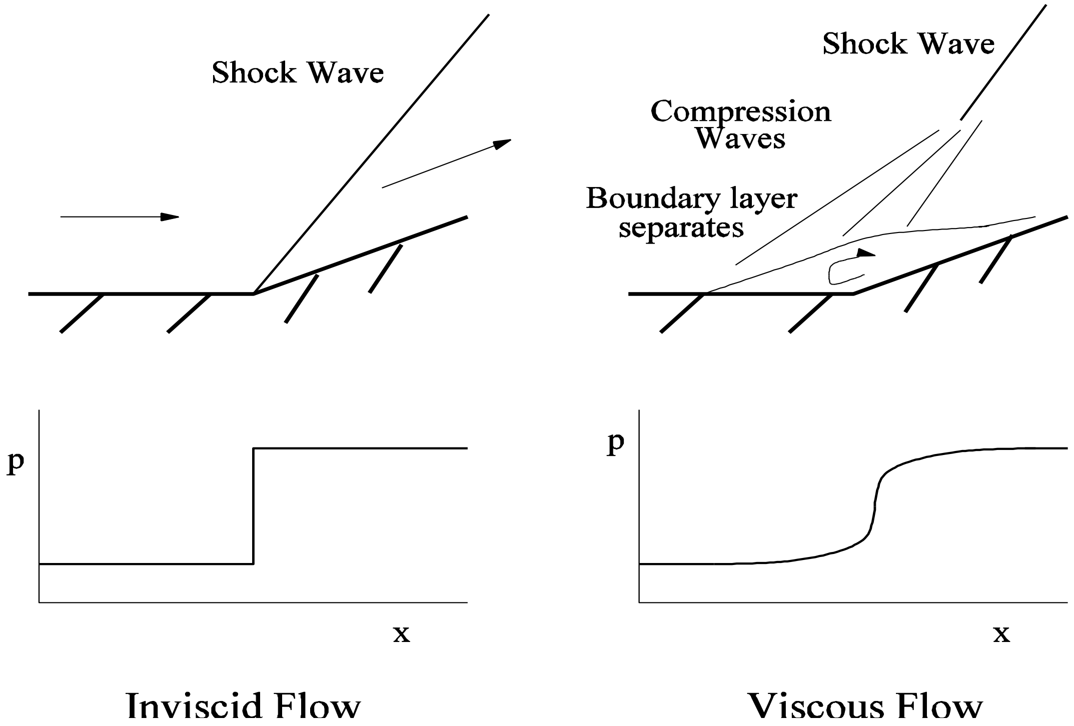
Two shocks

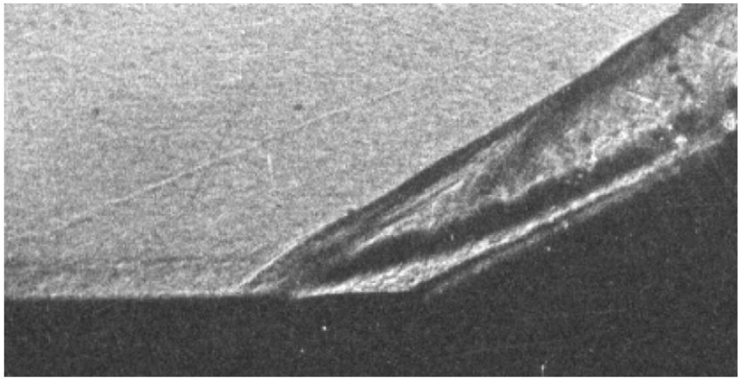
Merge at tip

3D shock+viscous effects



Oblique shock-boundary layer interaction



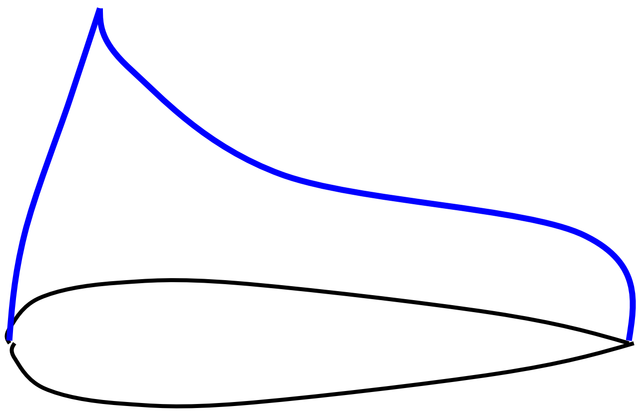


Drag Reduction

- We have already seen that the boundary layer properties effect the overall flow in terms of drag, separation, etc.
- If we can control the boundary layer, can control drag, at least to some extent
- Two examples: laminar flow by design, and by suction

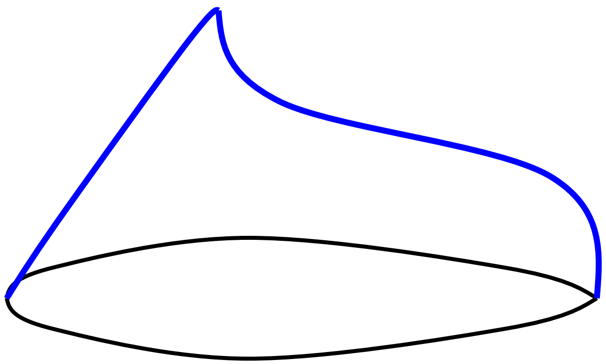
Laminar flow aerofoils

- Concept is simple enough
  - laminar flows have less drag (provided no separation)
  - More laminar boundary layer, less drag!
- Dates from about 1940
- Transition on an aerofoil is dominated by pressure gradient
- Can control the pressure gradient geometrically



BUT

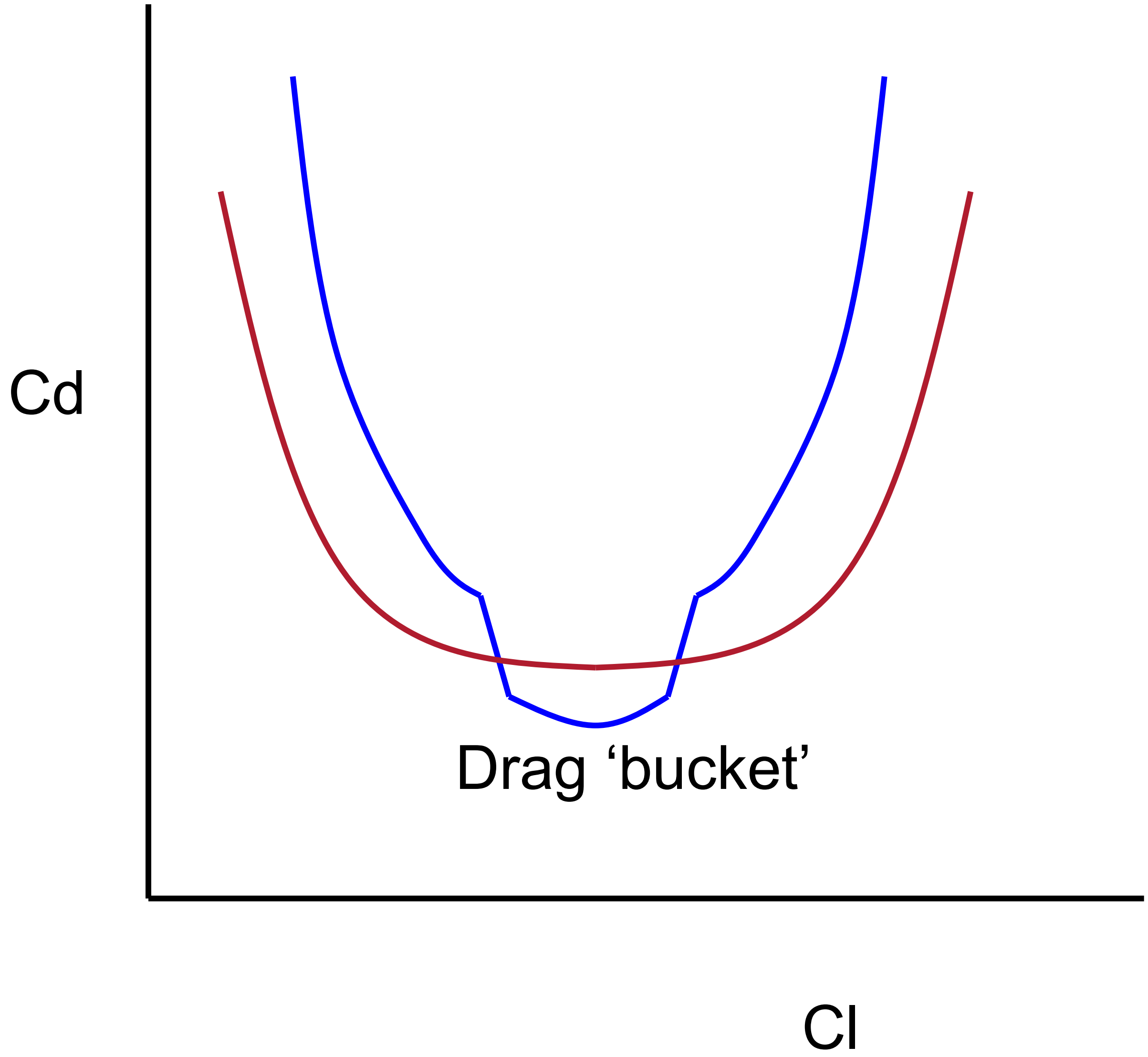
Susceptible to contamination – insects, rain, paint, dirt



By shifting thickness aft, reduce adverse pressure gradient = more laminar flow, less drag

However

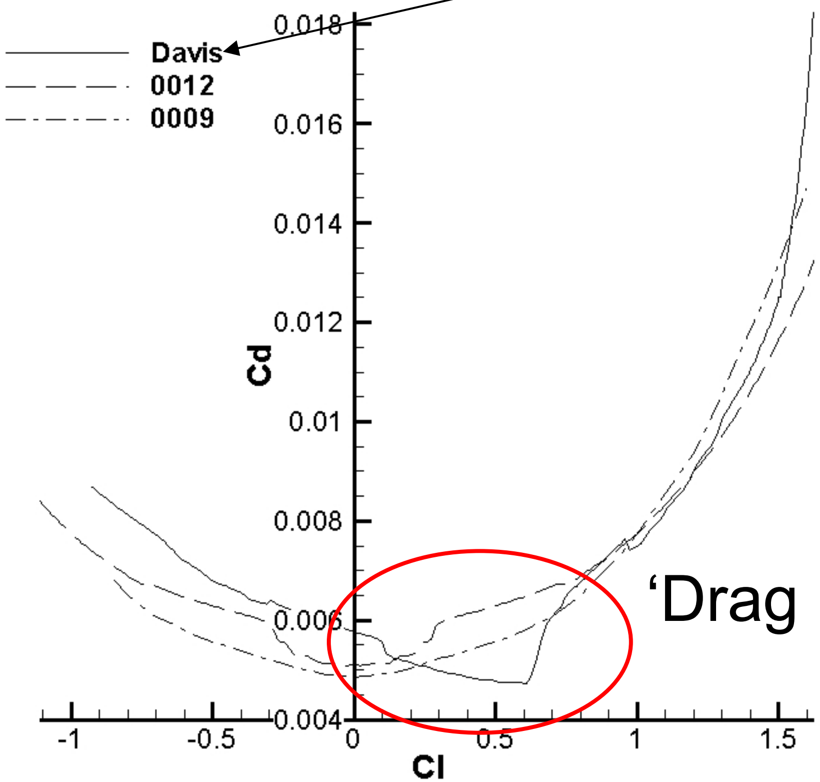
- Changing incidence moves Cp minima forward (as it does on all aerofoils
- In laminar case, moves more and faster
- Means that get good performance only for a narrow range of alpha (drag bucket)
- Not good for transonic flight – laminar bl more likely to undergo shock induced separation


Cd
Drag 'bucket'
Cl

B-17/B-24

The Davis Wing and the Problem of Airfoil Design: Uncertainty and Growth in Engineering Knowledge
Author(s): Walter G. Vincenti
Source: *Technology and Culture*, Vol. 27, No. 4, Special Issue: Engineering in the Twentieth Century (Oct., 1986), pp. 717-758 http://www.jstor.org/stable/3105326

Davis aerofoil showed larger region of laminar flow



'Drag bucket'

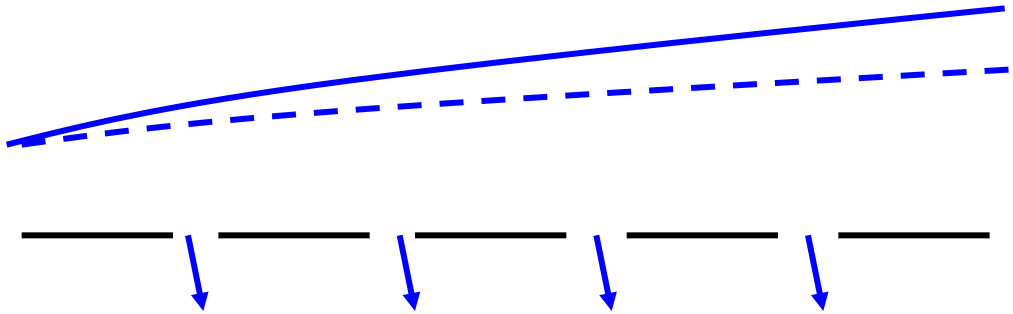
B-24
Davis

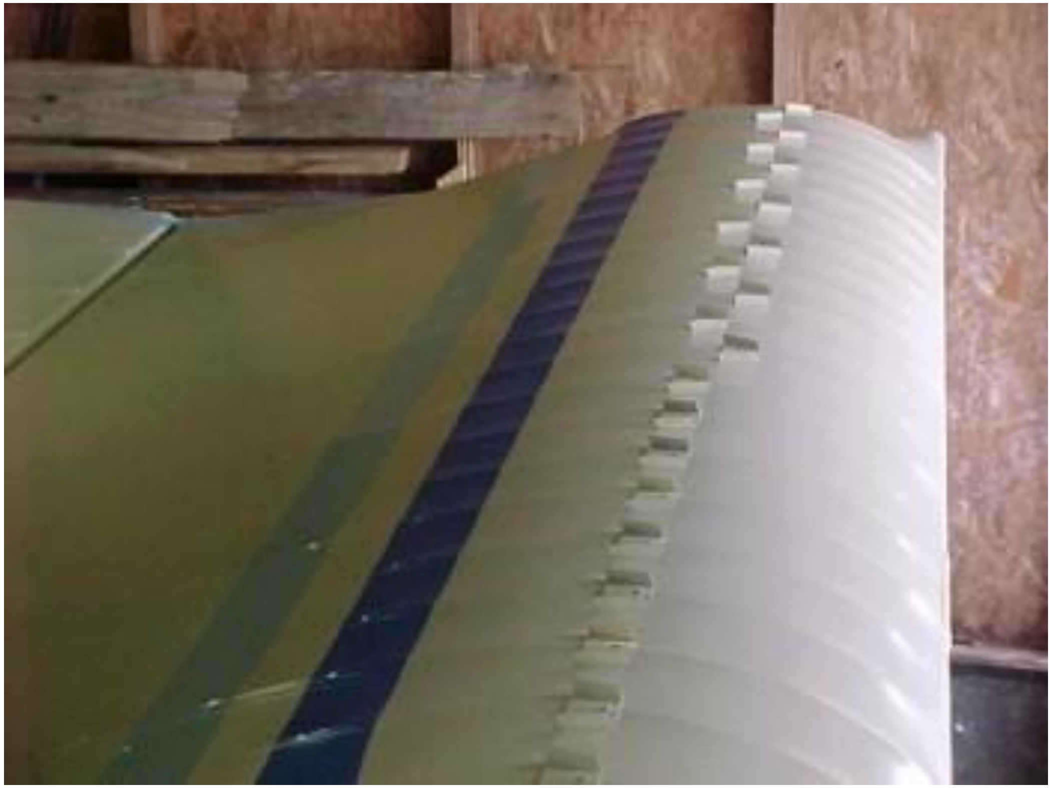
B-17
NACA

Any differences most likely due to AR difference (>11 compared to 7.5)

Boundary Layer suction

- If you take mass out of the boundary layer it behaves as if it had a lower Re
- Can do this by having a porous wall and sucking
  - is therefore an `active' measure, unlike laminar flow aerofoils which just rely on geometry
- extends amount of laminar flow
- requires power
  - Also problems of dirt, blockage of very small holes, etc!
  - Possibly 15% drag reduction – but system also requires power to run. Complicated to implement + maintenance costs





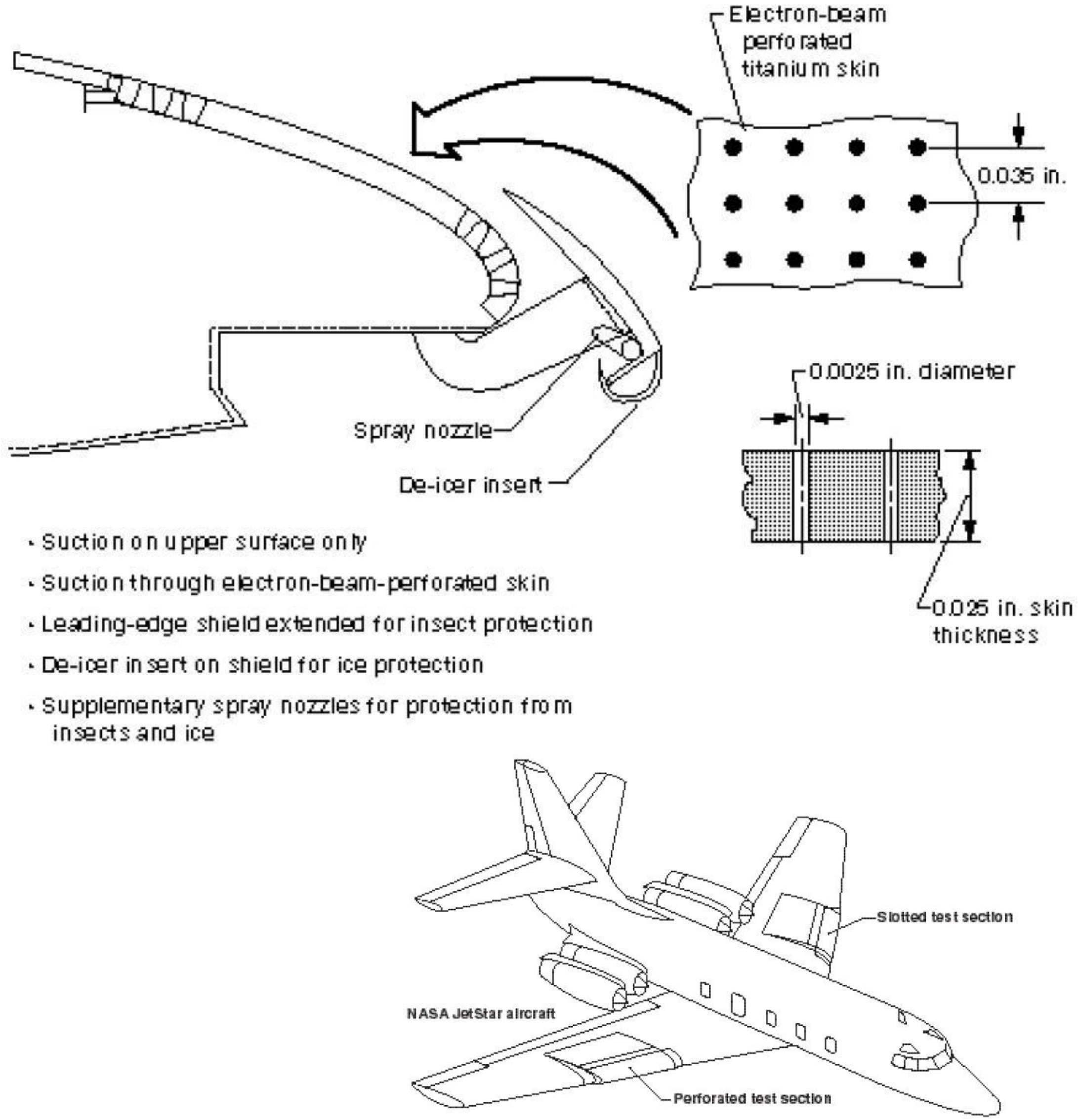


Figure 12. Leading-Edge Flight-Test program perforated test article.

Lift enhancement

- Can increase Cl by injecting high speed air across a flap, or over the leading edge of a wing
- Contributes to lift directly, and also prevents separation of the boundary layer, raising Cl_{max}

Boundary layer blowing

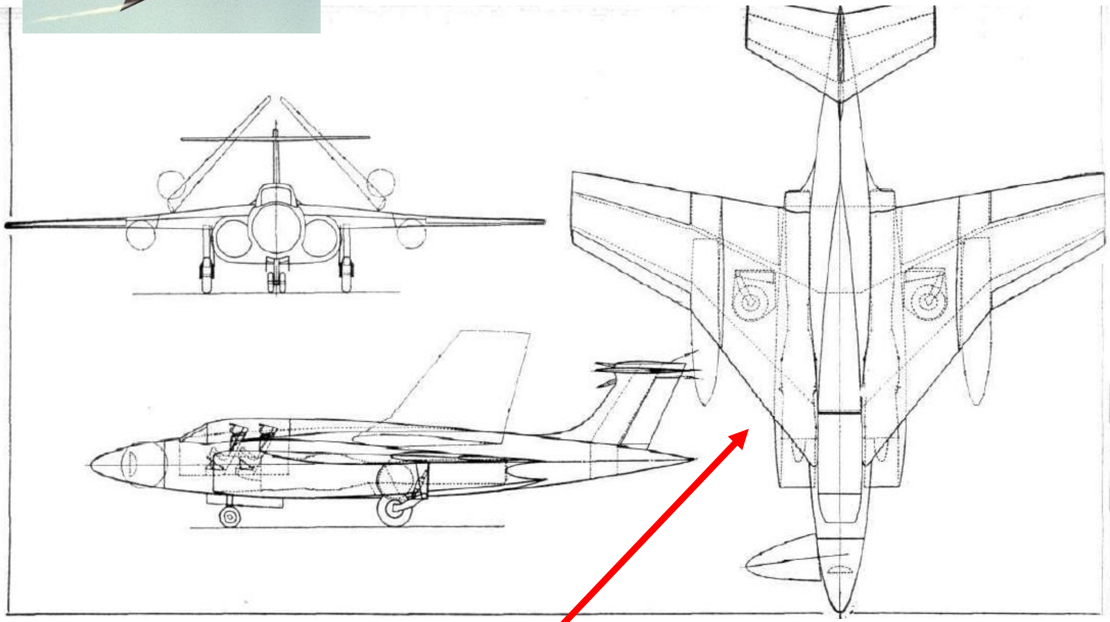
Stall speed<30mph!

Hunting H.126

Also works for de-icing!

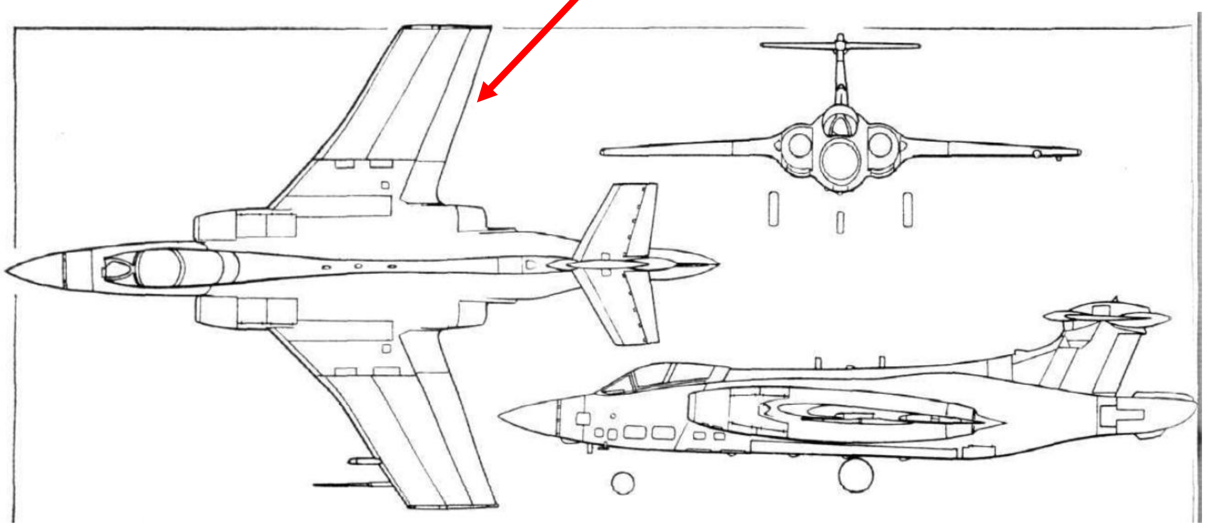
Buccaneer

Requirements – **carrier based** with **high top speed**



No bl blowing

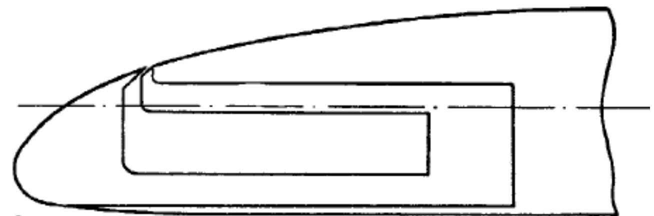
=big wing, low top speed



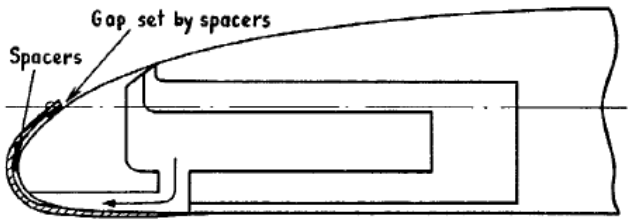
With bl blowing

=small wing, high top speed

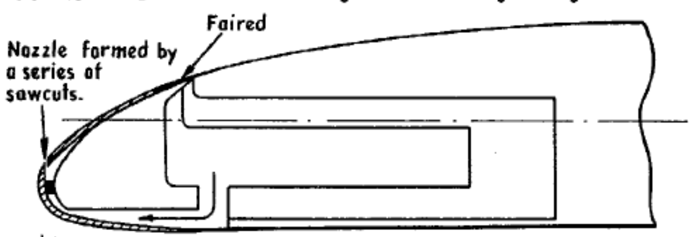
Buccaneer wind tunnel model arrangement



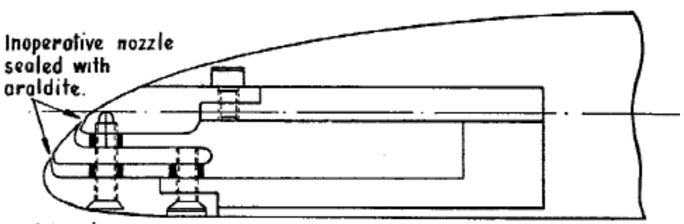
(b) 5% Chord nozzle.



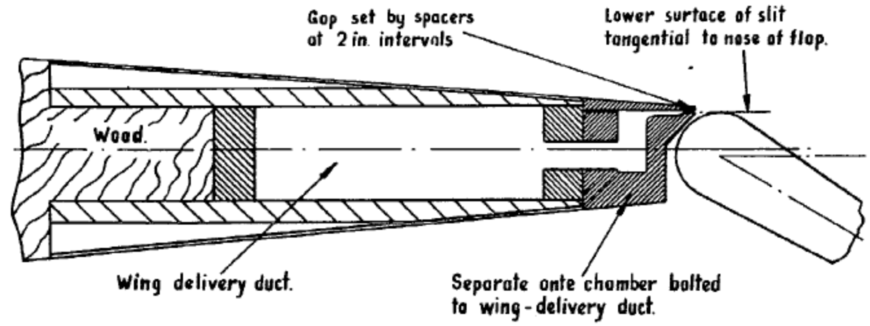
(c) $1\frac{1}{2}$% & 2% Chord nozzles. Original L.E. blowing arrangement.



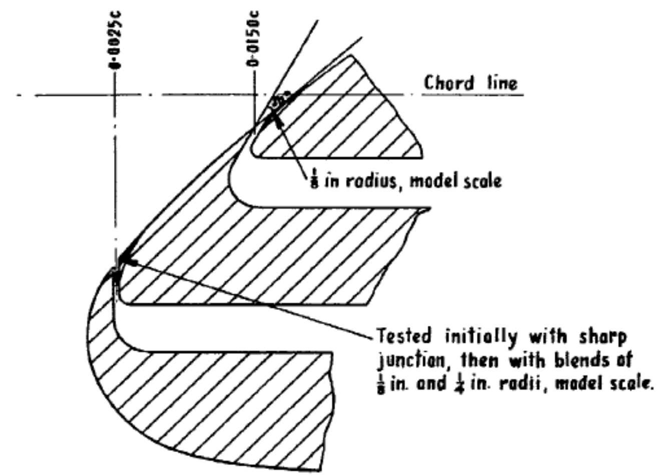
(d) $\frac{1}{4}$% Chord nozzle. Original L.E. blowing arrangement.



(e) $\frac{1}{4}$%, $1\frac{1}{2}$% Chord nozzles. Final L.E. blowing arrangement.

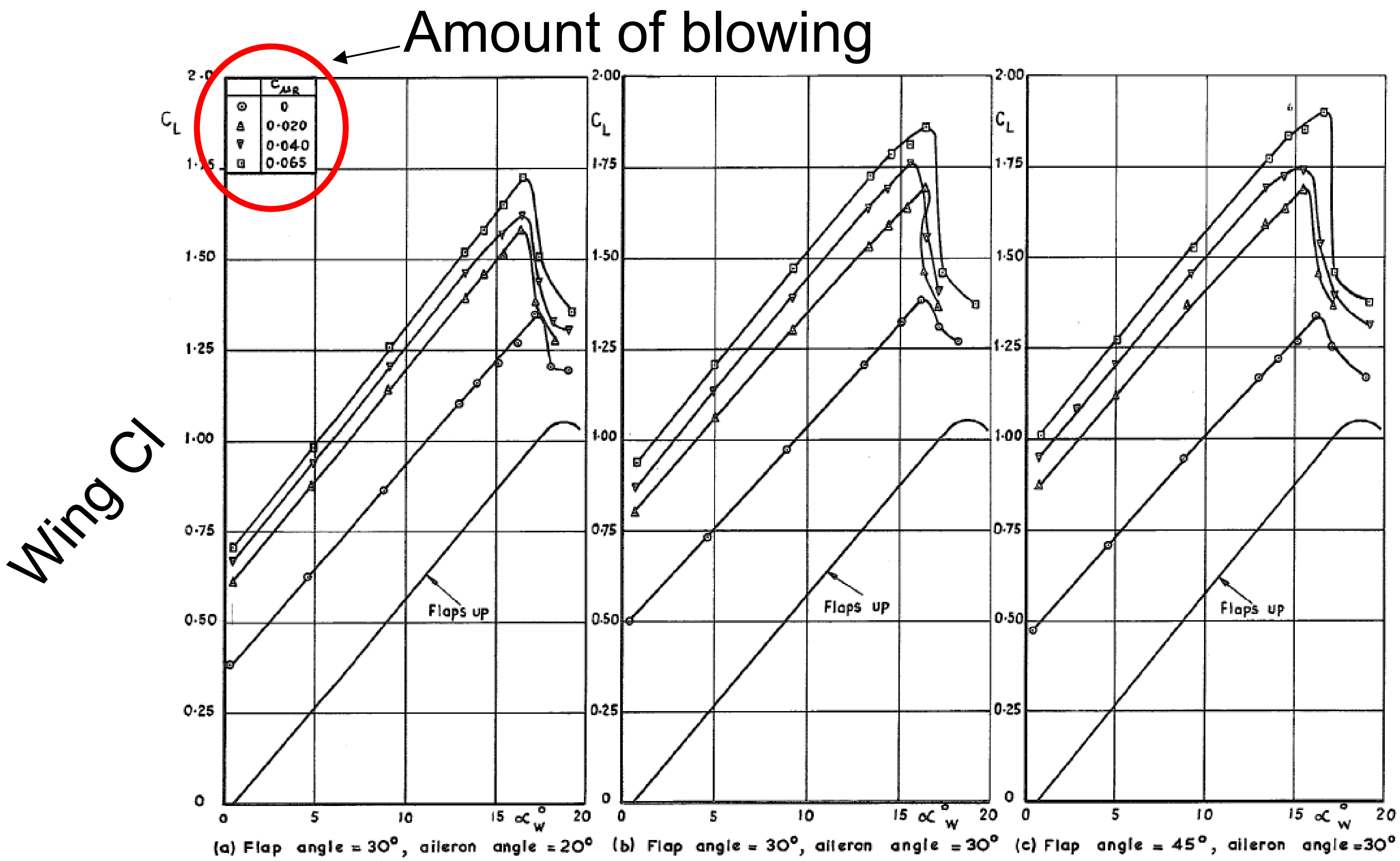


(a) Shroud nozzle and T.E. control arrangement.



(f) Enlarged section of final L.E. blowing arrangement

Effectiveness of flap bl blowing - Buccaneer



(aileron drooped to behave as a flap)