Department of Mechanical Engineering
University of Bath

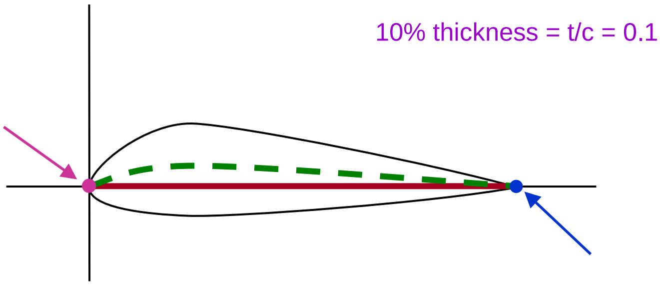
Laboratory Handout
Year 2 MEng

Aerofoil Experiment

Objectives

(i) Measure the pressure distribution over a NACA 2415 aerofoil for a range of angles of attack
(ii) Calculate the lift coefficient for the aerofoil and compare with published NACA data
(iii) Experimentally determine the effects created by a leading-edge slat
(iv) Understand the aerofoil characteristics in terms of fundamental fluid dynamics

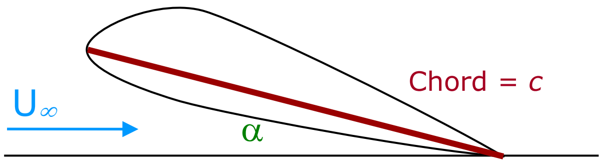
Defining an aerofoil



NACA four-digit aerofoil code

Example: NACA 2415

2 → 2% camber
4 → location of maximum camber = 40% x/c
15→ 15% maximum thickness (t/c)

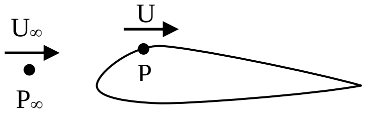


α = angle of attack

Generation of Lift

Aerofoil lift and drag are the resultants of force from pressure and shear stress on the aerofoil surface. These forces can be measured and integrated to find the net force on the aerofoil. Here the lift to drag ratio for a two dimensional aerofoil is very large, so for this experiment only the lift force will be calculated; furthermore since the lift is dominated by pressure forces, the shear stress distribution will able to be disregarded.

Bernoulli's equation for an incompressible, inviscid fluid:



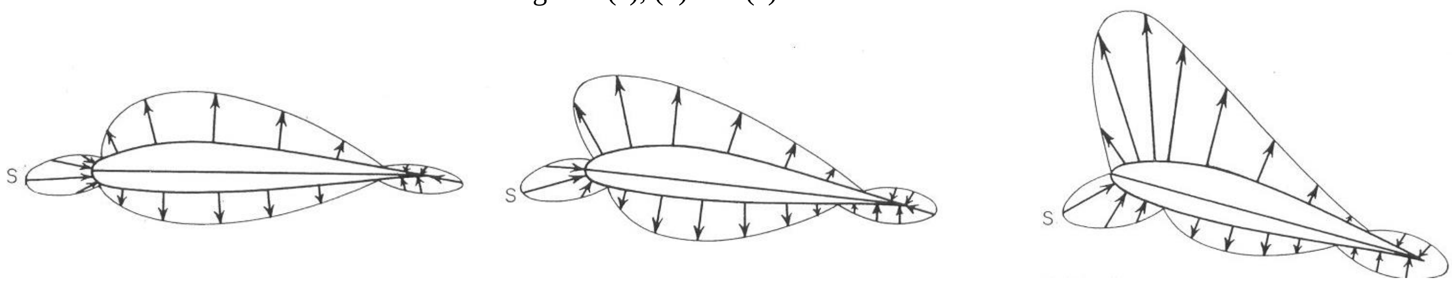
$$P_\infty + \frac{\rho U_\infty^2}{2} = P + \frac{\rho U^2}{2}$$

The local static pressure at any point on the aerofoil can be represented non-dimensionally in terms of a coefficient of pressure, C_P:

$$C_P = \frac{P - P_\infty}{\frac{1}{2}\rho U_\infty^2} \qquad (1)$$

where P = static pressure measured at surface
P_∞ = freestream static pressure
$\frac{1}{2}\rho U_\infty^2$ = dynamic pressure of the freestream

The creation of lift is due to the difference in pressure over the upper and lower surface of the aerofoil and can be illustrated as shown in Figure 1(a), (b) and (c).



(a) α=0° *(b) α=2°* *(c) α=8°*

Figure 1: Pressure arrows for different angles of attack (Length of arrow proportional to C_P)

The magnitude of pressure, or coefficient of pressure, at a point on the surface is indicated by the length of the arrow perpendicular to the surface. An arrow pointing to the surface indicates $C_p > 0$; an arrow away from the surface indicates $C_p < 0$. The total force on the aerofoil is calculated by integrating the pressure over the surface. The lift force varies as the angle of attack is increased or decreased.

The lift force (L) can be written in terms of a coefficient by dividing by the freestream dynamic pressure:

$$C_L = \frac{L}{\frac{1}{2}\rho U_\infty^2 S} \qquad (2)$$

For a two-dimensional aerofoil which spans the wind tunnel, the wing area $S = c$ x 1.0 m^2, where c is the aerofoil chord. In this experiment the *AerofoilLab* programme integrates the measured pressure data over the aerofoil surfaces to determine the lift coefficient. This can be plotted on a curve for various angles of attack (Figure 2).

Lift Curve

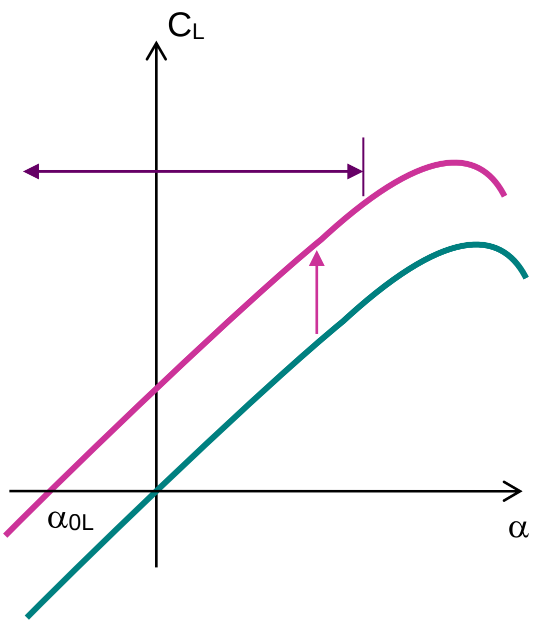


Figure 2: Lift Curve

Leading-edge slat

An aerofoil lift coefficient increases linearly with the angle of attack up to a maximum C_{Lmax}. A further increase in angle of attack leads to a precipitous drop in lift as the boundary layer separates; this is known as *stall.* To avoid separation, engineers incorporate *slats* into the leading edge of the aerofoil. A slat is essentially a thin, curved aerofoil that is deployed in front of the main aerofoil. In addition to the primary airflow over the main aerofoil, there is now a *secondary* flow through the gap between the slat and aerofoil leading edge. This secondary flow injects high momentum fluid into the boundary layer on the upper surface. Leading edge slats increase the stalling angle of attack and hence increases C_{Lmax}. Trailing-edge *flaps* are similar mechanisms and both are important for aircraft at take off and landing. Figure 3 illustrates a comparison between the boundary layer development with and without a slat. Further details of the boundary layer and flow separation are given in Appendix 3.

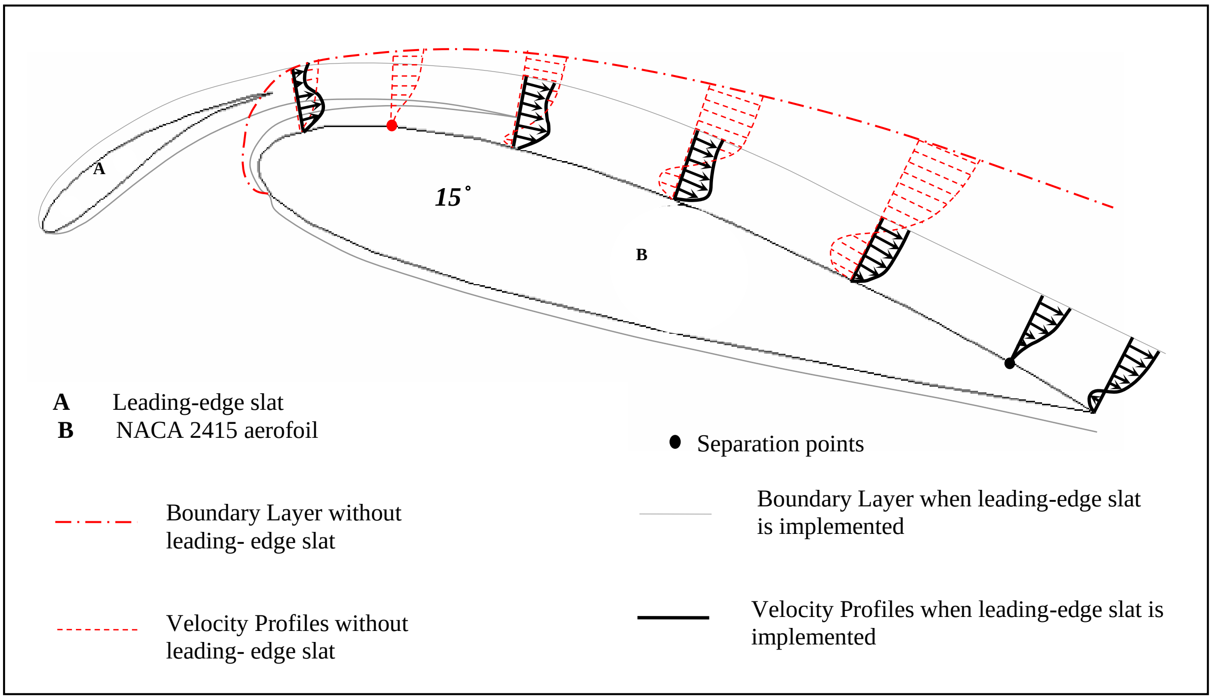


Figure 3: Velocity profiles through the boundary layer with and without a leading-edge slat

Aerofoil model, Wind Tunnel and Instrumentation

The NACA 2415 aerofoil (chord 127 mm) spans the working section of the 0.3 m open-return circuit wind tunnel. The test section walls act as end plates to maintain two-dimensional flow over the wing. The wing is supported by two integral spigots passing through bushes in the perspex windows of the test section and a clamp allows the aerofoil to be set at any angle of attack within the range of ±30°, measured using a pointer and protractor. The airspeed is measured using a Pitot-static tube upstream of the model. The wing is fitted with 33 pressure tappings in one chordal plane and the pressure distribution over the aerofoil is measured using a computer-controlled *Scanivalve* unit and transducer. The leading-edge slat is based upon the highly cambered NACA 22 aerofoil with chord of 38.1 mm.

Method

(i) Check that the pressure-tubes to the model and Pitot-static tube are connected correctly.
(ii) Start the tunnel and allow the speed to stabilise to approximately 20 m/s.
(iii) Using the LABVIEW programme *AerofoilLab*, collect C_P and C_L data over a range of angles.
(iv) Attach the leading-edge slat and recollect C_P and C_L data over a range of high angles of attack using LABVIEW programme *AerofoilLab_Slat*.
(iv) Plot the main data curves (see below) and discuss these with the laboratory demonstrator.

Presentation of Results

1 Plot C_L versus α and determine the slope of the linear region and the zero-lift angle of attack. Compare your measured slope with the theoretical slope of 2π increase in C_L per radian of α. Plot the NACA reference data (Table 1) on this graph. Calculate the Reynolds number of the flow in the wind tunnel and compare and discuss your measurements with those collected by NACA at different fluid-dynamic conditions. Viscosity of air at 25°C, $\mu = 1.8\times10^{-5}$ kg m^{-1} s^{-1}.
2 Plot the “pressure arrows” (see computer output for C_P data) around the aerofoil for α = 2°, 8°, 15° with a common scale for the length of arrows.
3 Add the data obtained with the leading-edge slat in operation to your C_L versus α graph and plot new “pressure arrows” for α = 15° with the slat.
4 Using the appendices describing *boundary layers* or the lecture notes, discuss how the fluid dynamics governs the lift characteristics at high angles of attack, using your data as evidence.

Report

Reports are not to exceed 2500 words (plus diagrams and tables). A concise *Summary* (probably the most important section of your report) should precede the introduction. The *Introduction* of your report should explain the importance and role of aerofoils in engineering science, leading to the objectives of the experiment. The *Experimental Apparatus and Procedure* section should provide a brief account of how C_L and C_P have been determined. The data should be tabulated clearly and the plots illustrated in the *Results* section, including a brief discussion of experimental uncertainty. Two figures should be presented: (i) C_L versus α (including the NACA data and effect of the leading-edge slat) and (ii) the pressure-arrow diagram with a common scale for the length of arrows. The figures should then be described and analysed in a separate *Discussion* section, making reference to Figure A6 and the theory in the appendices. The evidence, observations and explanations collected throughout the laboratory should be used and developed in this section (please note that Figures 3 and A6 may differ slightly to the results collected during your laboratory). The *Conclusions* should be succinct, relating back to the aims and objectives - probably 4-5 concise sentences or bullet points are sufficient. The “Boeing 747” questions, which carry 10% of the laboratory mark, must be completed and attached as an appendix.

Please take care in writing your report. Each paragraph and sentence should be re-read and re-worded until you have created a clearly-presented point. Write, read, re-write, re-read. Read through the assessment sheet on page 12 to make certain you are not missing any obvious points. Please give some thought to your graphs: are the scales appropriate; does the aspect ratio of the graph best present the data; should a grid be used; what symbols should be used (open/closed circles, diamonds, colour); should the data be connected by a line or curve, or just a portion of the data connected by a line; is the graph best presented to support the discussion? Be clear! Give it some thought! Don’t let your computer plotting package dictate terms.

The mark scheme is included on page 12; please use this to conduct your own self-assessment. Give yourself a mark (be honest), and if you’re not satisfied with it then go back and re-think your write up. Please also consider how long the report should be, make sure you have included the important points, but remember it is quality not quantity when writing a lab report.

Re	**3 x 10^6**	**6 x 10^6**	**9 x 10^6**
Angle (°)	**C_L**	**C_L**	**C_L**
-18		-0.900	
-17		-1.150	
-16		-1.350	
-14		-1.250	
-12		-1.050	
-10	-0.825	-0.825	-0.875
-8	-0.625	-0.625	-0.675
-6	-0.4	-0.400	-0.450
-4	-0.225	-0.225	-0.225
-2	0.000	0.000	0.000
0	0.200	0.200	0.225
2	0.400	0.400	0.425
4	0.625	0.625	0.625
6	0.800	0.800	0.850
8	1.000	1.025	1.075
10	1.200	1.200	1.275
12	1.300	1.400	1.425
14	1.425	1.500	1.570
16	1.300	1.600	1.650
18	1.175	1.300	1.575
20	1.075	1.125	1.350
22	1.025	1.075	1.250
24	1.050	1.000	1.325

Table 1: NACA data - Lift coefficients for different Re numbers at various angles of attack

Appendix 1: Boeing 747 Questions

Question 1

a. Calculate the Reynolds number (based on chord) for this experiment. Note the aerofoil chord, c = 127 mm and the viscosity of air at 15 ^{o}C, $\mu = 1.8 \times 10^{-5}$ kg m^{-1} s^{-1}.

b. What was the range of Reynolds numbers for the NACA experiments? Comment.

Question 2

A Boeing 747-400 cruises at Mach 0.86 at an altitude of 35,000 feet. At mid-cruise the aircraft weight is 3.20 MN and the total thrust from four engines is 185 kN.

Data at 35,000 feet: static temperature and pressure are 219 K and 23.8 kPa, respectively.

(γ = 1.4, R = 287 J/kgK; at 219 K, $\mu = 1.7 \times 10^{-5}$ kg m^{-1} s^{-1})

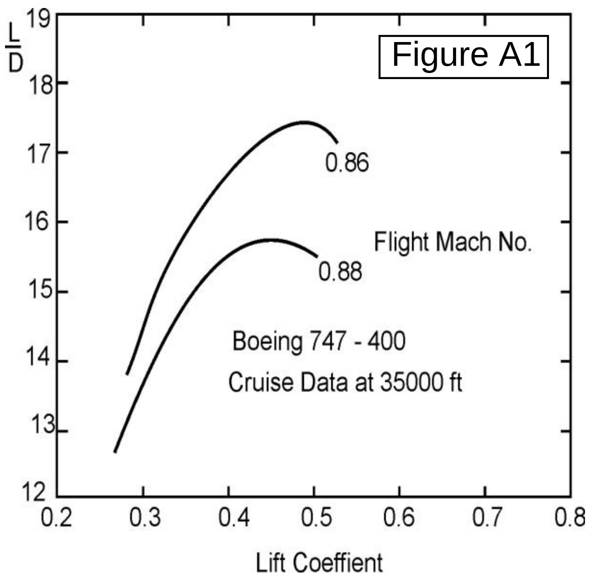
a. Determine the Reynolds number of the 747, based on a mean chord of 9.0 m.

b. Determine the lift coefficient and lift-to-drag ratio (L/D) if the wing area is 510 m^2.

$$C_L = \frac{W}{\frac{1}{2}\rho V^2 S}$$

$$a = \sqrt{\gamma R T}$$

c. Compare your calculations with the flight data for the 747-400 shown in Figure A1. With reference to the boundary layer, explain why the lift-to-drag ratio reduces significantly as the Mach number increases from 0.86 to 0.88.

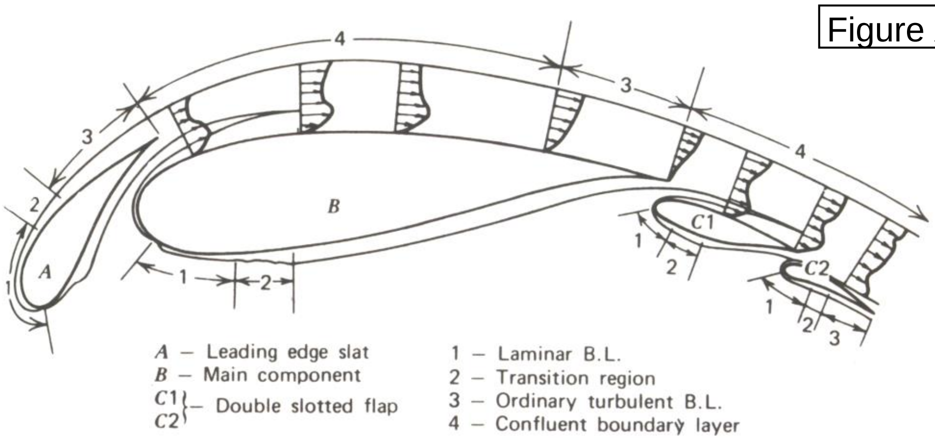


d. Due to fuel burn, the weight of the 747 reduces to 2.4 MN when it lands with a sea-level airspeed of 60 m/s using mechanical high-lift devices. (ρ_{SL} = 1.2 kg/m^3)

Determine the lift coefficient at landing.

e. A sketch of typical boundary layer velocity profiles for aerofoils employing mechanical high-lift devices is shown in Figure A2. With reference to the boundary layer, discuss how these slats, vanes and flaps increase lift.

Figure A2



Appendix 2: Evidence

Fill in the boxes to describe the evidence collected from the laboratory.

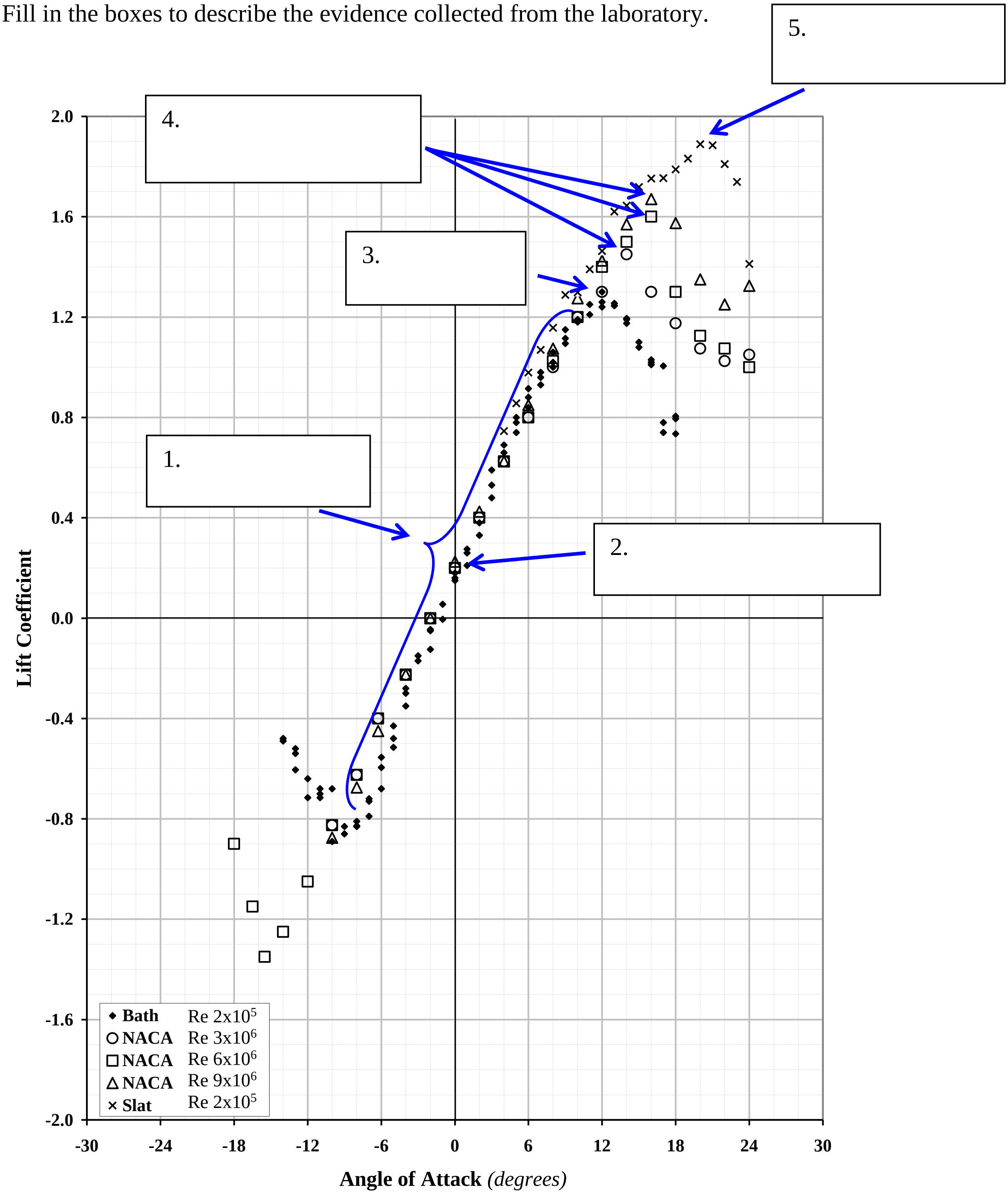


Figure A3: Lift coefficient vs angle of attack

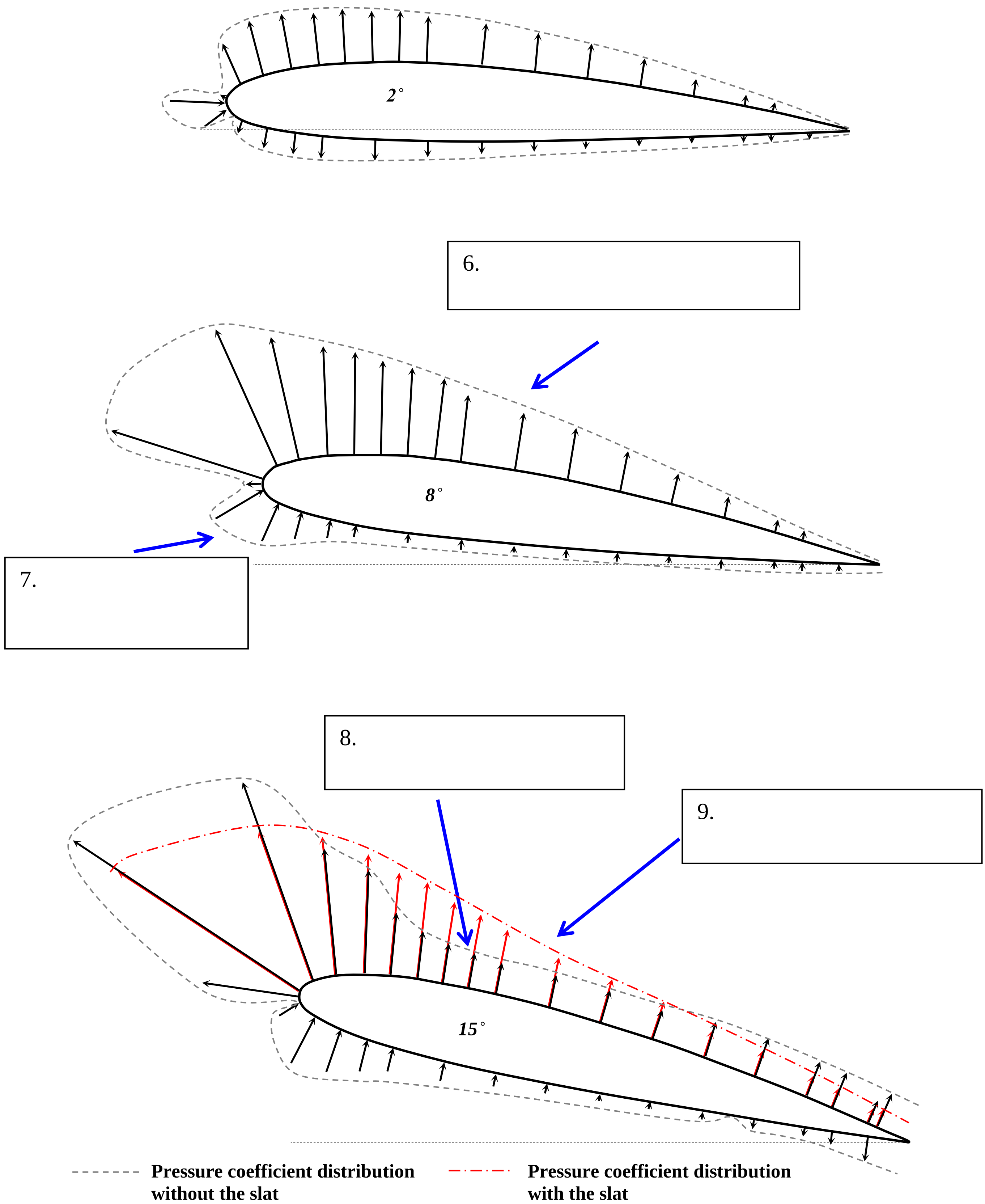


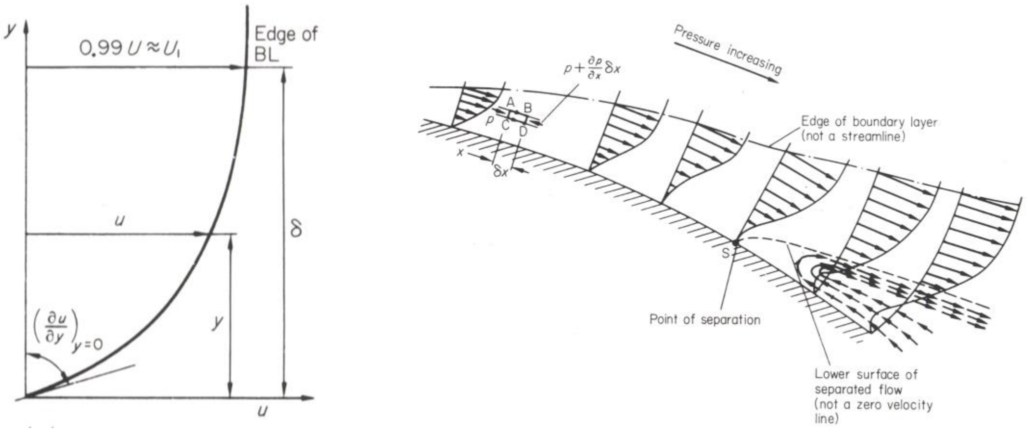
Figure A4: Pressure coefficient distribution over the NACA 2415 aerofoil at various angles.

Appendix 3: Boundary Layers

Viscosity is an inherent property of any natural fluid and it is the means by which a fluid *sticks* to solid surfaces, so that the relative velocity at any solid boundary is zero. Fluids cannot support a discontinuity of velocity, consequently there is, close to a surface, a region in which the velocity increases rapidly from zero and approaches the velocity of the mainstream. This region is known as the *boundary layer*. See Figure A5. The boundary layer merges into the mainstream with no sharp line of demarcation but, for convenience, the boundary layer is considered to extend to a distance δ from the surface such that the velocity u at that distance is 99% of the local mainstream velocity U_1.

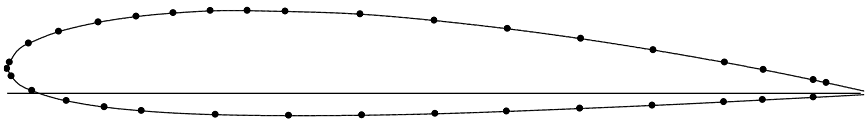
The behaviour of a boundary layer in a positive pressure gradient, i.e. pressure increasing with increase in distance downstream, may be considered with reference to Figure A6. This shows a length of surface which has a gradual but steady convex curvature, such as the surface of an aerofoil beyond the point of maximum thickness. In such a flow region, because of the retardation of the mainstream flow, the static pressure in the mainstream will rise (Bernoulli's equation). The variation in static pressure along a normal to the surface through the boundary layer thickness is essentially zero, so that the pressure at any point in the mainstream, adjacent to the edge of the boundary layer, is transmitted unaltered through the layer to the surface. In the light of this, consider the small element of fluid marked ABCD. On face AC, the pressure is p, while on face BD the pressure has increased to p +dp. Thus the net pressure force on the element is tending to retard its velocity. This retarding force is in addition to the viscous shear which act along AB and CD and it will continuously slow the element down as it progresses downstream.

This slowing down effect will be more pronounced near the surface where the elements are remote from the accelerating effect, via shearing actions, of the mainstream, so that successive profile shapes in the stream-wise direction will change as shown. Ultimately, at a point S on the surface, the profile slope $(\partial u/\partial y)_W = 0$. Apart from the change in shape of the profile it is evident that the layer must thicken rapidly under these conditions, in order to satisfy continuity within the layer. Downstream of point S, the flow adjacent to the surface may well be in an upstream direction, so that a circulatory movement, in a plane normal to the surface, may take place near the surface. A line (shown dotted in the figure) may be drawn from the point S such that the mass flow above this line corresponds to the mass flow ahead of point S. The line represents the continuation of the lower surface of the upstream boundary layer, so that, in effect, the original boundary layer separates from the surface at point S. This is termed the separation point. The large wake created by the separated boundary layer dramatically changes the flow field. If an aerofoil were at a sufficiently large angle of incidence, the separation of the boundary layer may take place not far downstream of the maximum suction point, and a very large wake will develop. This will cause such a redistribution of the flow over the aerofoil that the large area of low pressure near the upper surface leading edge is seriously reduced, with the result that the lift force is also greatly reduced. This condition is referred to as aerodynamic *stall*.

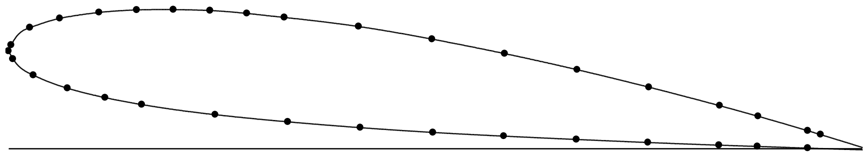


Figures A5 and A6: boundary layer separation

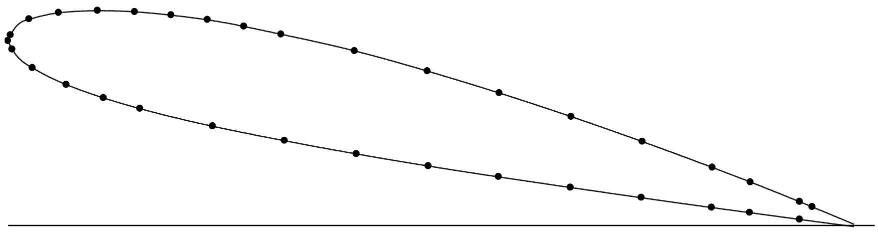
Aerofoil sketches for pressure-arrow diagrams



2°



8°



15°

Pressure Surface	**x/c**	0.010	0.042	0.083	0.125	0.167	0.250	0.333	0.417	0.500	0.583	0.667	0.750	0.833	0.878	0.936				
Suction Surface	**x/c**	0.000	0.010	0.043	0.080	0.125	0.167	0.208	0.250	0.291	0.333	0.417	0.500	0.583	0.667	0.750	0.833	0.878	0.936	0.950

Year 2 Aerofoil Laboratory Assessment Sheet, 2024-25

Assessor: _______

Student: .... **Date:** ____________

	A	B	C	D	E	Comments
Summary						☐ No reference to significant conclusions ☐ Too short ☐ Overview of report not provided ☐ Unclear and/or not succinct ☐ Focussed on unimportant or irrelevant content
Introduction						☐ Lacks interest or originality ☐ Objectives not stated ☐ Importance of aerofoils to engineering not explained ☐ Writing is unclear or lacks structure ☐ Focussed on unimportant or irrelevant content
Expt / Procedure						☐ No explanation of how C_L and C_P obtained ☐ Detail out of proportion with remainder of report ☐ Writing is unclear or lacks structure
Results/ Discussion						☐ Discussion of graphs lacks coherent structure ☐ No discussion of aerodynamic stall ☐ Inadequate reference to fluid dynamics / boundary layer ☐ Inadequate comparison with NACA data at different Re ☐ No discussion of experimental uncertainties ☐ No discussion of the effect of leading edge slat
Conclusions						☐ Unclear and/or not succinct ☐ Main conclusions incorrect ☐ No link to objectives ☐ Focussed on unimportant or irrelevant content
Figures and Tables						☐ Graphs not numbered or have inappropriate titles ☐ Some/all figures and tables not referred to in the text ☐ Graph axes labelled inappropriately ☐ Scales on graphs not appropriate ☐ Orientation or aspect-ratio of graphs not appropriate ☐ Graphs not plotted clearly or symbols poorly chosen ☐ Inappropriate number of significant figures in data ☐ Poorly presented data
Clarity						☐ Not written in the 3rd person, past tense ☐ Writing is unclear or lacks structure ☐ Your work has not been adequately proof-read ☐ Poor grammar
Appendices						☐ Not completed *Boeing 747* questions

General comments:

Mark:

A:70+ B: 60-69 C: 50-59 D: 40-49 E: 39-