PART 1B EXPERIMENTAL ENGINEERING

SUBJECT: FLUID MECHANICS & HEAT TRANSFER EXPERIMENT T3
LOCATION: HYDRAULICS LAB (Gnd Floor Inglis Bldg) (LONG)

BOUNDARY LAYERS AND DRAG

OBJECTIVES

a) To measure the velocity profiles of laminar and turbulent boundary layers growing on a flat plate.

b) To relate the momentum loss of the fluid in the boundary layers to the skin friction drag on a body.

c) To measure the drag on a bluff body, such as a sphere, and to understand why this is much greater than the skin friction drag.

INTRODUCTION

Drag induced on bodies moving through fluids is of major economic importance because it determines the energy consumption of most types of transport - especially road vehicles, ships and aircraft.

The drag arises from two distinct causes. Firstly from the shear stress acting on the surface of a body, which is called the skin friction. Secondly from the pressure acting normal to the surface of the body. If the average pressure over the rear of a body is lower than that over its front then there is a net pressure drag. The relative importance of these two types of drag depends on the shape of the body. For streamlined bodies, such as an aircraft wing, the skin friction drag dominates, whilst for a non-streamlined body (often called a bluff body), such as a truck, the pressure drag is very much larger than the skin friction drag.

When a body moves relative to a fluid the fluid in immediate contact with the surface of the body is brought to rest relative to the body. The fluid some distance away from the surface is still moving and so there is a layer of fluid near to the surface of the body which is being sheared. When a fluid is sheared shear stresses are set up proportional to the rate of shearing. Note the distinction from solids where the shear stress is proportional to the shear strain - in a fluid it is proportional to the rate of shear strain. Note also the distinction between the shear stress in a fluid and that arising from sliding friction between solids, the latter depends on the normal stress whilst the former does not depend on the pressure.

The constant relating the shear stress to the rate of shear strain is the fluid viscosity, μ.

$$\tau = \mu \frac{dV}{dy}$$

where V is the fluid velocity and y is the distance normal to the surface.

The layer of fluid that is slowed down by friction near to the surface of a body is usually very thin (typically about 1% of the length of the body) and is called the boundary layer. The behaviour of boundary layers can be very complex and is still an area of active research.

However, the most important feature is that the motion of the fluid in the boundary layer may be either steady and streamlined (called laminar) or unsteady and chaotic (called turbulent). The type of boundary layer obtained in practice depends on many factors (e.g. surface roughness) but the most important one is a dimensionless number called the Reynolds Number which is a measure of the relative importance of pressure forces and viscous forces. Since in incompressible flow pressure changes are of magnitude ρV^2 and viscous stresses are of magnitude $\mu V/L$,where L is the length scale of the body, the Reynolds number is

$$\mathrm{Re} = \frac{\rho V L}{\mu}$$

At high Reynolds numbers, typically > 10^5, the flow in boundary layers tends to be turbulent and at lower values it tends to be laminar. The exact point of transition between the two types of flow depends greatly on the geometry and on many other factors and is still not easily predictable. In this experiment we will study both types of boundary layer and determine which gives the higher skin friction.

Pressure drag is indirectly a consequence of the boundary layer behaviour. If the streamlines around a symmetrical body, such as a sphere, were symmetrical, then the pressure would be the same on the upstream and downstream side and the pressure drag would be zero. However, the existence of the boundary layer causes the flow to be asymmetric even when the geometry is symmetrical and as a result the pressure on the downstream side tends to be lower than on the upstream, giving rise to a pressure drag. If the body is streamlined then the pressure asymmetry is small, as is the thickness of the body over which it acts, and the pressure drag is likely to be less than the skin friction drag. However, on non-streamlined (bluff) bodies the boundary layers tend to break away from the surface on the downstream side of the body, giving rise to a large asymmetry in the flow and pressure distribution, and a pressure drag that is much greater than the skin friction drag.

The drag is usually turned into a dimensionless drag coefficient, C_D where

$$C_D = \frac{Drag}{0.5 \rho V^2 A}$$

where V is the flow velocity ρ the fluid density and A the cross-sectional area of the body. Dimensional analysis tells us that, for a given shape of body in incompressible flow, this dimensionless drag coefficient is a unique function of the Reynolds number

$$C_D = Fcn(\mathrm{Re})$$

where the form of the function can, in general, only be determined by experiment. Typical values of C_D are in the range 0.05 for streamlined bodies to 1.0 for bluff bodies. For an aircraft wing the drag coefficient is usually based on the wing's chord rather than its thickness and so the value is much lower, typically 0.005.

PART A. BOUNDARY LAYERS

APPARATUS

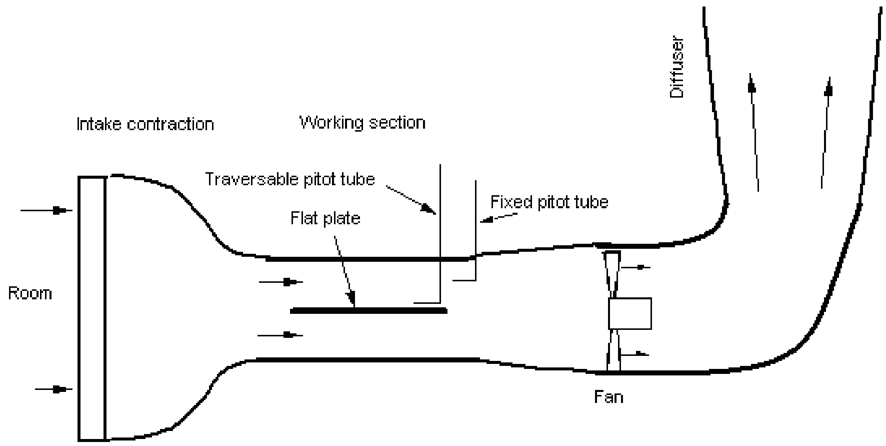


Fig. 1 Layout of the Wind tunnel

The layout of the apparatus is sketched above. Air from the laboratory is sucked through the wind tunnel by an electrically driven fan at its exit. The working section is of square cross section with the flat plate located at its centre. The walls of the working section are parallel The working section and fan are connected by a gradually diverging section known as the diffuser. The velocity in the working section is of order 12m/s and so the flow may be considered incompressible, i.e. ρ = constant. The flow velocity and length of the flat plate have been chosen so that the Reynolds number is in the transitional regime between laminar and turbulent flow. If the boundary layer on the plate suffers no disturbance then it will remain laminar but if it is disturbed by a "trip" at the leading edge of the plate then it will become turbulent.

INSTRUMENTATION

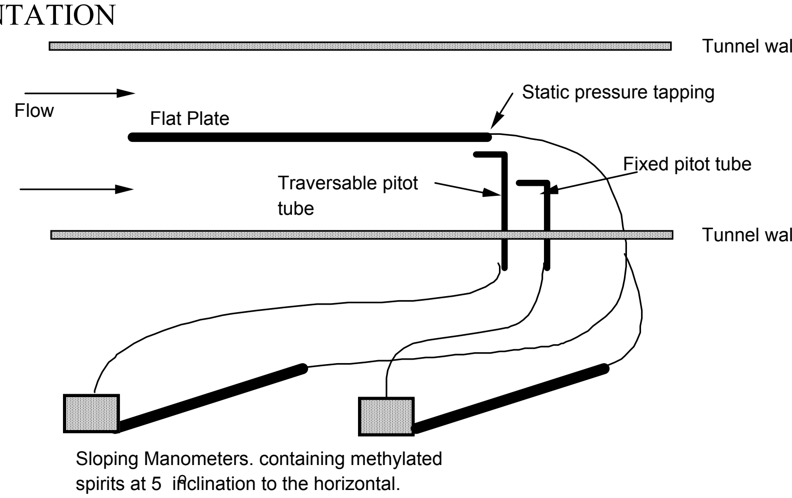


Figure 2. layout of the instrumentation

The velocity distribution in the boundary layer is measured by traversing it with a small pitot tube whose end is flattened so that it can measure very close to the surface. The velocity in the free stream flow outside the boundary layer is measured by a fixed pitot tube. These pitot tubes record the stagnation pressure (or total pressure) of the local flow, in order to convert this to velocity we need to know the static pressure. This is very nearly constant throughout the working section and is measured by a pressure tapping flush with the surface of the plate near to its trailing edge. The difference between the stagnation and static pressure can be converted to velocity via Bernoulli's equation.

$$p_{stagn} - p_{static} = 0.5\,\rho\,V^2$$

Where V is the local flow velocity.

The pressure difference is measured by sloping manometers filled with methylated spirits and inclined at an angle θ of about 5^o to the horizontal. If the height of the manometer column is Δh then

$$p_{stagn} - p_{static} = 0.5\,\rho\,V^2 = \rho_{\text{meths}}\, g\,\Delta h \sin\theta$$

Since the air density ρ is constant the ratio of velocity in the boundary layer to that in the free stream, is

$$\frac{V_{bl}}{V_{fs}} = \sqrt{\frac{\Delta h_{bl}}{\Delta h_{fs}}}\ .$$

This is the quantity that we will plot and so there is no need to convert the manometer readings to velocities except to estimate the Reynolds number.

PROCEDURE

1. Make sure that the movable pitot tube attached to the top of the tunnel is raised so as to be well away from the measuring region. Also make sure that the nose trip is removed from the leading edge of the flat plate so that you start with a laminar boundary layer.

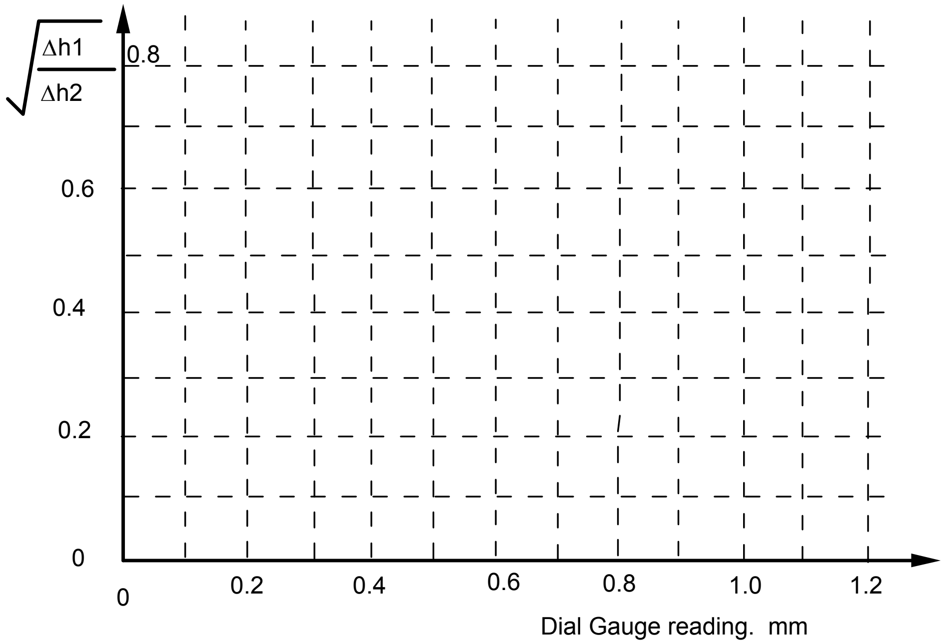
2. Adjust the levels of the manometer and the height of the reservoir so that both tubes read zero when there is no flow.

3. Turn on the power to the fan and use the variable transformer to gradually increase the fan speed until the manometer recording the mainstream flow reads about 10 cm.

4. Turn on the LCD display on the dial gauge and traverse the moveable pitot tube towards the surface of the plate until it reaches its stop. Set the zero of the dial gauge at this position and ***do not touch the zero setting again***. The tip of the probe is now touching the surface of the plate but it is probably slightly bent by the contact force and so will not start to move away from the surface until you have turned the traverse mechanism some distance.

5. The most difficult part of the experiment is finding the position of the probe tip relative to the surface. We do this by very gradually moving the probe away from the surface, taking measurements of flow velocity at each position, and then extrapolating them to the point where the velocity is zero, which corresponds to the surface of the plate. Move the probe away from the surface in steps of about 0.1 mm, at each point record the dial gauge reading and manometer heights Δh_1 and Δh_2. Note that it takes about 15 seconds for the manometer to stabilise after a change of probe position, if the readings are fluctuating take an average over about 30 seconds. Record the results in your notebook and plot them on Graph 1 below ***as you proceed***. Check any points that do not lie on a smooth curve.

Continue this process until the dial gauge reading is 1.0 mm, by which time you should have a clear near-linear region of the graph which you can extrapolate to zero velocity. This extrapolation gives the true position of the surface of the flat plate.



Graph 1. Velocity profile near to the plate surface.

6. You can now continue the traverse taking steps of about 0.25 mm, continue to record the results but there is no need to plot them as you proceed. When the probe is more than 2.5 mm from the surface you can increase the step to 0.5 mm. Continue to take readings until the manometer connected to the traversing pitot tube no longer changes. The two pitot tubes should read closely the same at this condition.

7. Observe the motion of the tufts of down attached to the lower side of the plate and use the moveable pitot tube connected to the stethoscope to "listen to" the pressure fluctuations in the boundary layer compared to those in the free stream.

8. The boundary layer you have just traversed was a laminar one. When both you and the group working on the other side of the tunnel have finished the laminar boundary layer traverse, place the nose cap over the leading edge of the plate. This will trip the boundary layer to make it turbulent. Observe the motion of the down tufts and listen with the stethoscope, noting any changes from the laminar boundary layer.

9. Repeat the traverse with the turbulent boundary layer. Once again take initial steps of 0.1 mm and plot the points on the graph above ***as you proceed*** until a clear curve is discernable. Check any points which do not lie on the curve. The graph should ***not*** be close to a straight line in this case so do not try to extrapolate it to zero velocity. Increase the spacing to 0.25 mm until you are more than 3 mm from the surface beyond which you can take steps of 1mm. When more than 10mm from the surface take steps of 2 mm. Again continue until the edge of the boundary layer is reached.

PART B. DRAG OF SPHERES

In this part of the experiment you will measure the drag on spheres by measuring the velocity with which they fall through viscous liquids. Once dropped into the liquid the spheres very soon reach a terminal velocity where the difference between their weight and the buoyancy force on them is equal to the drag. By weighing the spheres and measuring their diameter to calculate their volume and hence the Archimedian upthrust we can obtain the drag.

Equating the drag to the weight minus the upthrust the dimensionless drag coefficient can be written as

$$C_D = \frac{mg - \rho_{liquid} g \pi D^3 / 6}{0.5 \rho V^2 \pi D^2 / 4}$$

This coefficient is a unique function of the Reynolds number but the form of the function can, in general, only be determined by experiment. Not surprisingly, for a simple body such as a sphere many experiments have been done and the accepted results are shown plotted in Graph 4 which covers 7 orders of magnitude of Reynolds number.

The object of the experiment is to obtain a few points to compare with this graph.

PROCEDURE

It is difficult to get accurate results from this experiment unless you choose the combination of sphere and liquid carefully. If the sphere drops too quickly (say less than 4 seconds) it is not possible to time the fall and hence obtain the velocity accurately. Hence large steel spheres in low viscosity liquids such as water should be avoided. Also if the density of the sphere is very close to that of the liquid then the upthrust will nearly equal the weight and the net drag will be the small difference of two larger numbers and is again of low accuracy. Hence small plastic spheres in glycerine should also be avoided. In fact some of them float !

You should aim to obtain results from 3 different combinations of sphere and liquid. Record the results on Table 1 below, which can also be used for the calculations.

1. Weigh the sphere on the electronic balance provided.

2. Measure its diameter very carefully with the micrometer.

3. Drop the sphere gently into the cylinder and time its fall between the two marks, 1m apart, with the stop watch.

4. Note the fluid used.

Fluid	Weight of sphere gm	Diam of sphere mm	Time to drop sec	Velocity m/s	Upthrust N	Drag N	Drag Coeff.	Reynolds Number

Table 1. Results and calculations from the dropping spheres experiment.

CALCULATIONS AND WRITING YOUR REPORT

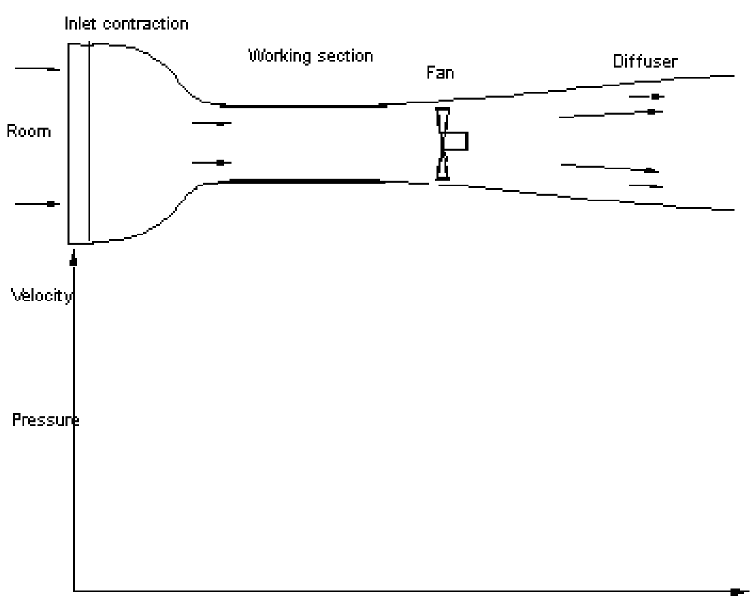
Your report should include:

– **Summary**: a brief summary of aims and objectives of the experiment

– **Readings and results:** This lab sheet with the graphs completed should be attached to your note book.

– **Calculations and Discussions:**

1. Sketch the velocity distribution and the pressure distribution along the wind tunnel on the graph below. Explain the purpose of the diffuser.



2. Taking the slope of the manometers to be 5^o and the density of methylated spirits to be 815 kg/m^3 , use Bernoulli's equation to calculate the free stream velocity in the tunnel.

3. Taking the viscosity of air to be air to be 1.75 $\times 10^{-5}$, the density of the air to be 1.2 kg/m^3 and the length of the plate to be 0.735 m calculate the Reynolds number of the flow.

4. Comment on the differences in the motion of the down tufts and the noise from the stethoscope for the two types of boundary layers.

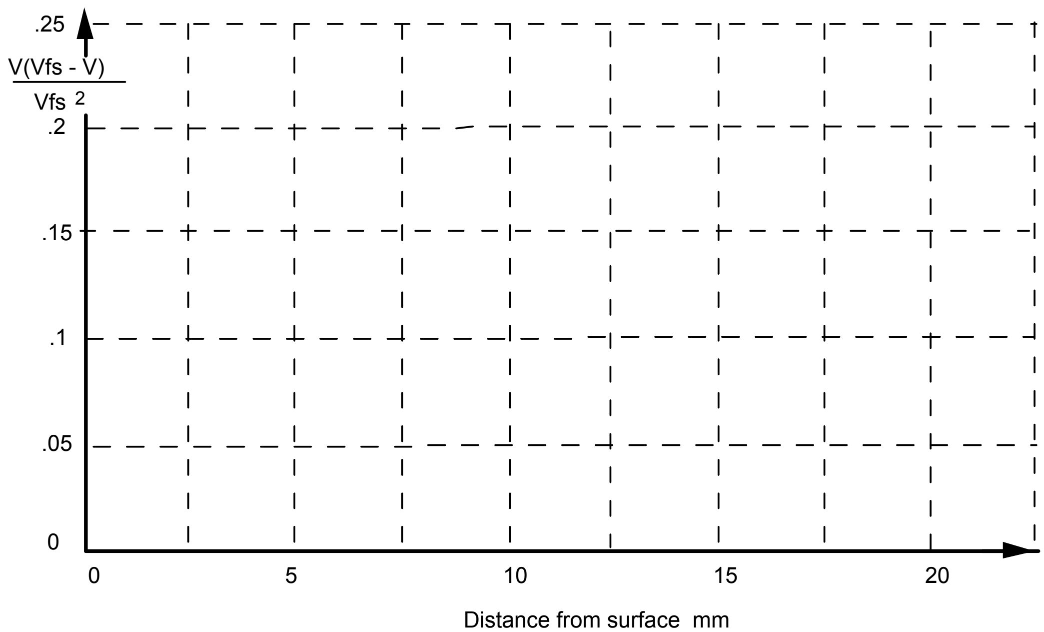
5. For both boundary layer traverses convert the dial gauge readings to the true distance from the plate surface using the extrapolated surface position obtained from the laminar boundary layer on Graph 1. Plot the results for both the laminar and the turbulent boundary layer on Graph 2 (at end of this lab sheet). Both graphs should now pass through the origin.

6. A particle of fluid with mass dm and velocity V within the boundary layer has lost momemtum $dm(V_{fs} - V)$, where V_{fs} is the free-stream velocity. The mass flow rate per unit span of the plate through a width dy of the boundary layer is $\rho\, V\, dy$ so the rate of loss of momentum of the fluid within the boundary layer is

$$\dot{M} = \int_0^{\delta} (V_{fs} - V)\rho V dy$$

where δ is the boundary layer thickness. Because the pressure around the plate is uniform this rate of loss of momentum must equate to the total skin friction drag on one side of the plate.

Use your experimental results for V/V_{fs} for ***the turbulent boundary layer*** to plot a graph of $V(V_{fs} - V)/V_{fs}^2$ against distance from the surface on the Graph 3 below. You need not plot all the experimental points, just enough to get a good curve. Note that the graph should pass through zero at the surface of the plate and at the edge of the boundary layer, force it to satisfy these conditions even if your experimental points do not. Then do the same for the laminar boundary layer.



Graph 3. Momentum loss integral

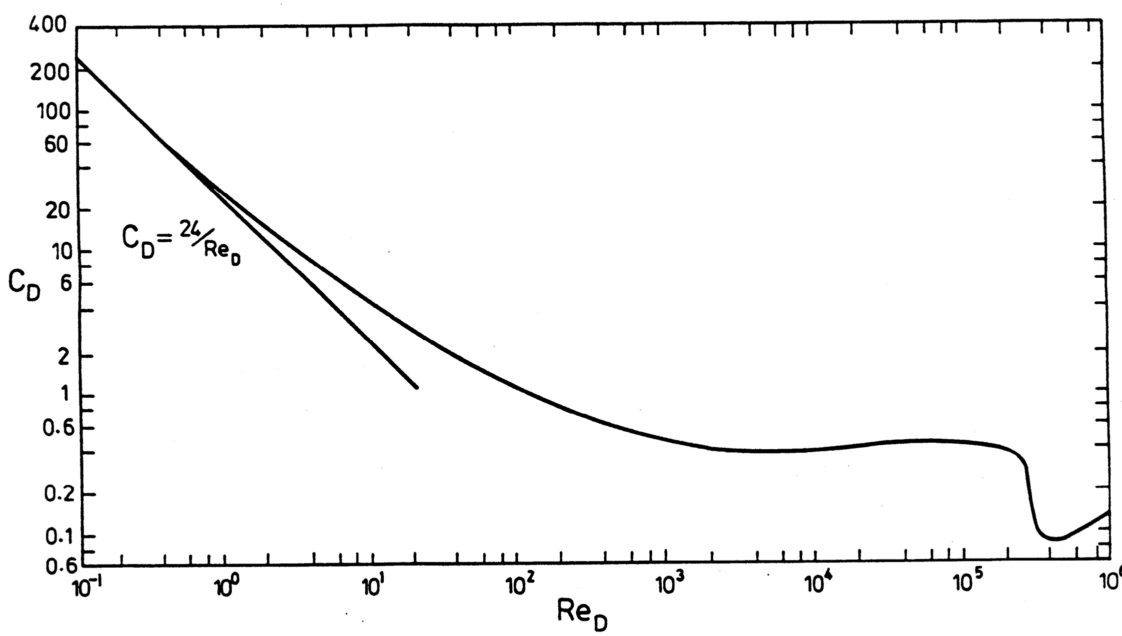
Estimate the area under the graph either by counting squares or by using Simpson's rule. This gives the value of $\int_0^\delta \left(\frac{V(V_{fs} - V)}{V_{fs}^2} \right) dy$. To obtain the rate of loss of momentum per unit span we must multiply it by ρV_{fs}^2. Hence estimate the total skin friction drag on one side of the plate in Newtons per metre span.
Sketch in a few points from the laminar boundary layer on the above graph and, without doing any calculations, use them to decide whether the skin friction drag of the laminar boundary layer is greater or less than that of the turbulent one.

7. A thin layer of fluid very close to the surface remains laminar even when the bulk of the boundary layer is turbulent. Hence the shearing stress acting on the surface of the plate is equal to $\mu (dV/dy)_{y=0}$ for both types of boundary layer. Taking the viscosity of air to be 1.75×10^{-5} use the slopes of the velocity profiles at the surface from Graph 1 to estimate the skin friction (i.e. the shear stress acting on the surface) of both the laminar and the turbulent boundary layer in N/m^2. Compare the results with an estimate of skin friction drag obtained from the rate of momentum loss in Q6 above. Would you expect them to be the same?

8. For your experiments with the falling spheres complete Table 1. ***Be very careful to convert all units to SI units before using them to find the dimensionless numbers.*** You may use the following average values for the density and viscosity of the fluids at room temperature. Note the actual values of viscosity vary significantly with temperature.

	Water	Oil	Glycerine
Density kg/m^3	1000.	870	1261
Viscosity kg/m/s	1.0×10^{-3}	48.7×10^{-3}	1513×10^{-3}

Graph 4 below shows the trend of results from many experiments on the drag of spheres. Plot your points on this graph. Check your calculations very carefully if values of C_D are more than an order of magnitude different from those on the graph. Suggest reasons for any significant discrepancies.



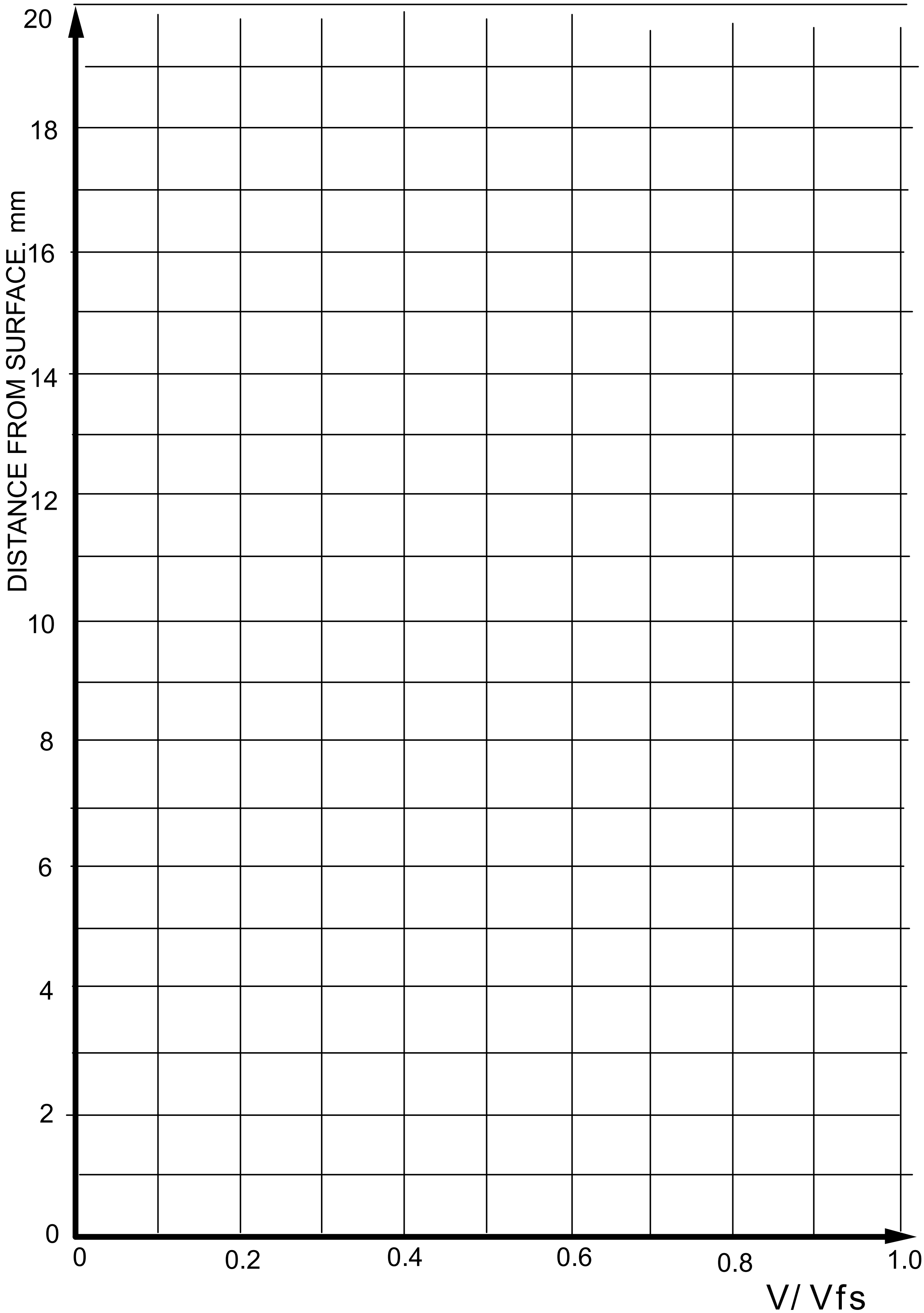
Graph 4 Drag coefficient of spheres as a function of Reynolds number.

9. The drag coefficient of an aerofoil or a flat plate is usually expressed as $C_D = \dfrac{\textit{Drag per unit span}}{0.5\rho V_{fs}^2\, L}$ where L is the length of the plate which is 0.735 m. Convert your value for the rate of momentum loss per unit span in the turbulent boundary layer to this definition of drag coefficient and plot it at the plate Reynolds number on Graph 4 above. Comment on the result.

The sudden drop in drag coefficient at Re about 2×10^5 on the above graph is an interesting consequence of boundary layer behaviour. If there is time ask the demonstrator to explain it.

– **Conclusions:** Summarise your main findings

(lx/jl, Sept. 2015)


DISTANCE FROM SURFACE, mm
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
0.6
0.8
1.0
V/ Vfs

GRAPH 2