Fundamental FLUIDS

Fundamental Fluids

MATRIX

CP2599

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Contents

Fundamental FLUIDS

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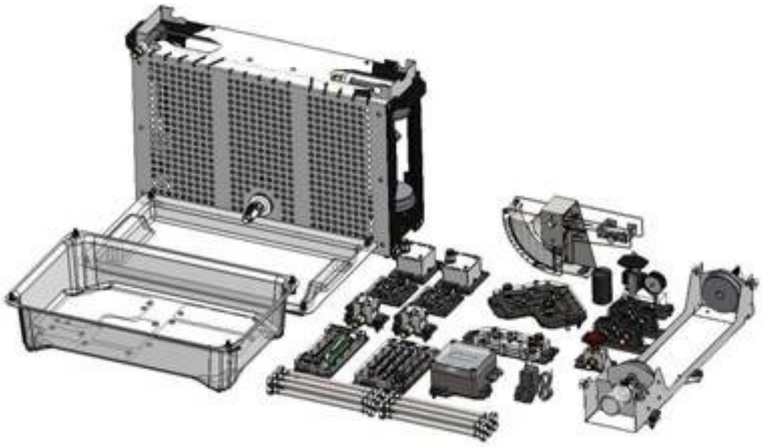
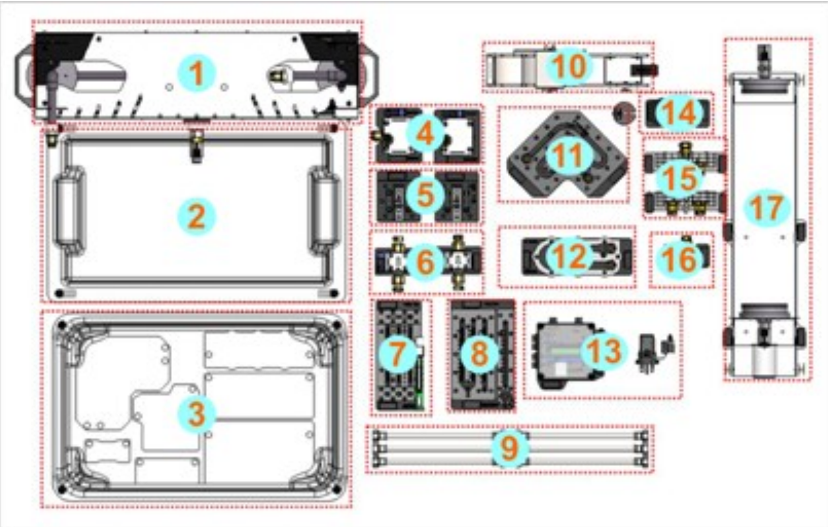
The kit



Contents



Item	Name	Item	Name
1	Fluids workstation	10	Centre of pressure kit
2	Drip tray	11	Losses in bends module
3	Storage cover	12	Venturi tube module
4	Centrifugal pump modules (2)	13	Data control module
5	Differential pressure sensors (2)	14	Bourdon gauge calibration kit
6	Turbine flow meters (2)	15	Tee piece / manifold (2)
7	Multitube manometer	16	Gate valve module
8	Inclined manometer module	17	Viscosity apparatus
9	300mm hoses (12)		

The kit includes a 24V plug-top power supply and leads, shown in the images above next to the Data control module.

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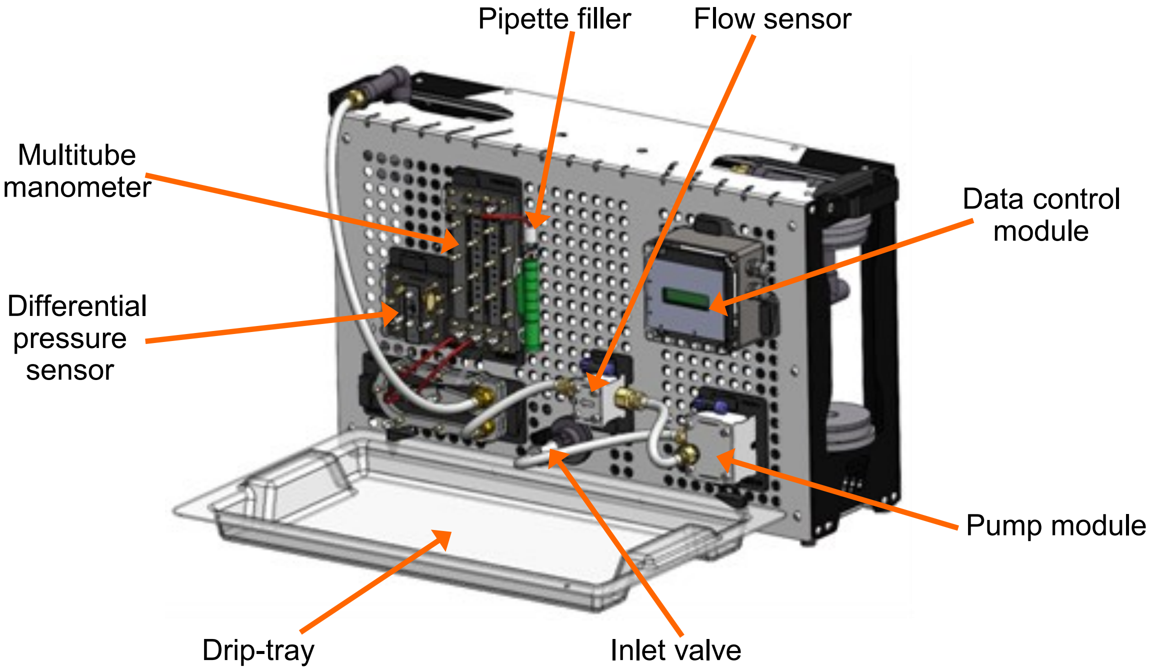
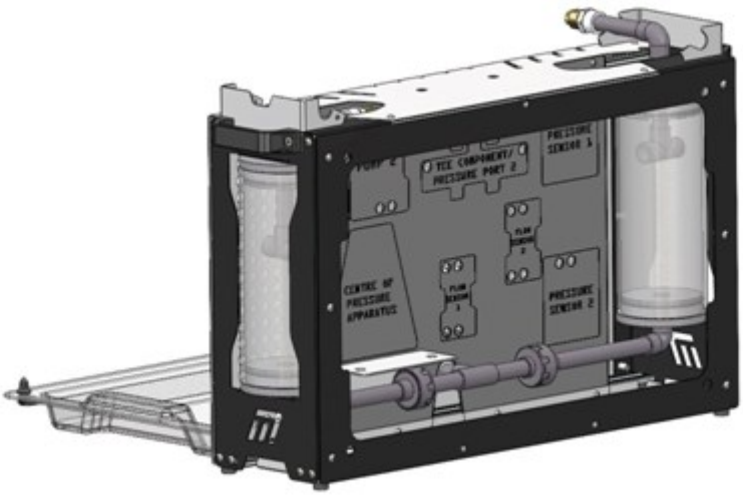
Introduction

The workstation - typical setup:



Modules clip on to the workstation in the desired position using ‘swell latches’.
Once the apparatus is assembled, pour between 2 and 3 litres of water into one of the tanks. (It does not matter which - they are linked together and will fill together.)
The drip tray has a capacity of 6 litres and so can comfortably hold the entire contents of both tanks.

Rear view:



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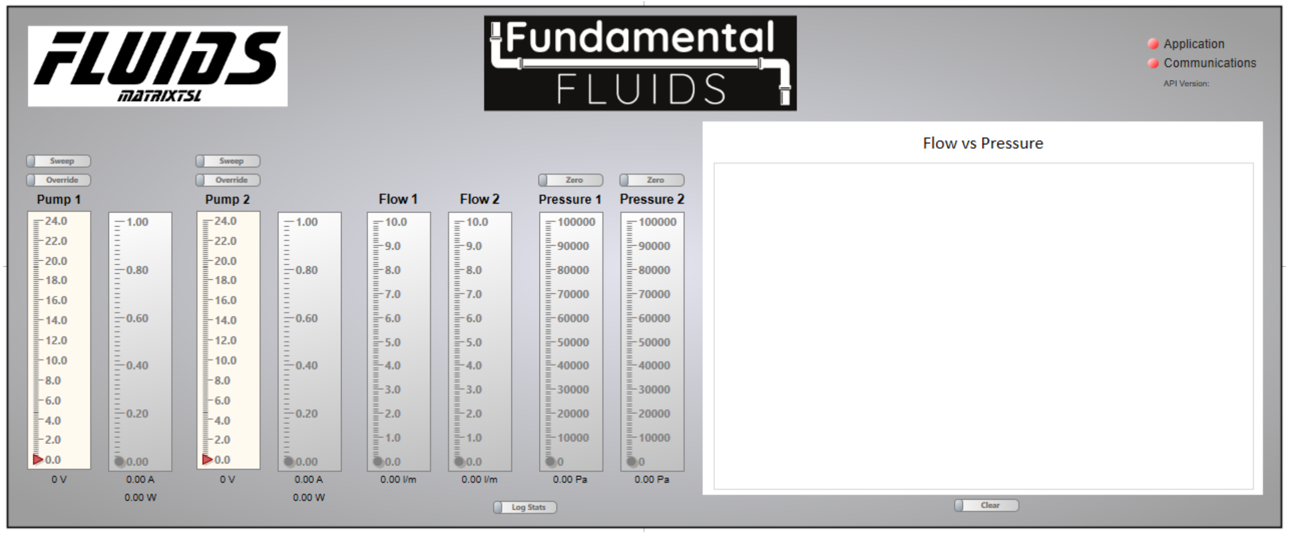
‘Fluids’ control application

The application communicates with devices on the Fluids workstation, performing tasks like controlling pumps and generating flow-rate and pressure readings.

Part of the application screen is shown below.



It communicates through the data control module with up to two pumps, two flow meters and two differential pressure sensors. Clicking on the ‘Go’ button initiates this communication. The two indicators, ‘Application’ and ‘Communication’, near the top left corner of the image above, turn green when this communication is established.

The ‘Zero’ buttons above the ‘Pressure 1’ and ‘Pressure 2’ scales allow the respective pressure sensors to be initialised (set to zero). Before taking readings, with the pumps turned off, the relevant differential pressure sensor should be initialised.

There are three ways to switch on a pump:

- slide the cursor up the voltage scale to the required point;
- click on the ‘Override’ button and insert the required voltage in the box that opens;
- click on the ‘Sweep’ button - the application then ramps the voltage delivered to the pump from high ’Start’ voltage to low ’Cut-off’ voltage in voltage steps as specified in the app. Properties panel.

The data recorded during one of these operations can be obtained in one of two ways:

- following a ‘sweep’ operation, the readings are transferred to the folder containing the ‘Fluids’ control app.;
- following taking a set of discrete readings, click on the ‘Log Stats’ button - again, the data is in the folder containing the ‘Fluids’ control app.

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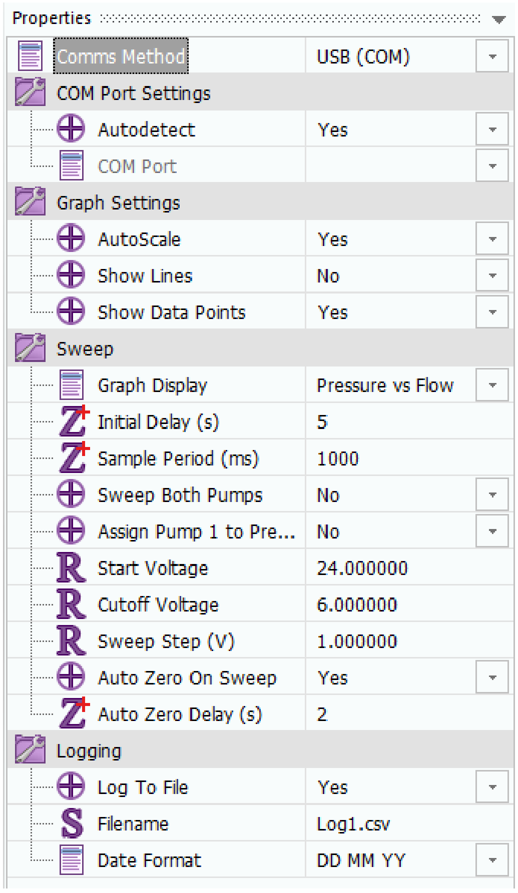
Introduction

'Fluids' control application ...

The application properties include settings for :

- an initial delay to allow flow to settle;
- the time between samples;
- the range of voltages and step-size used during 'sweeps';
- the location and filename of the log file where the data from the investigation is stored.

Typical settings are shown in the dialogue box opposite, though these will be changed from investigation to investigation.

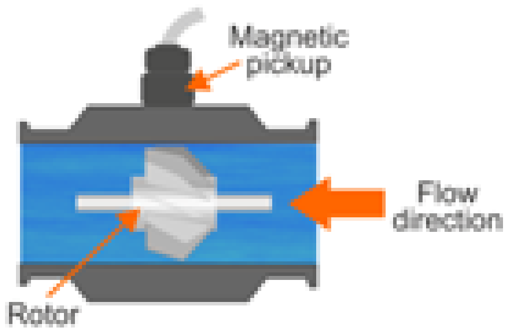


Properties	
Comms Method	USB (COM)
COM Port Settings	
Autodetect	Yes
COM Port	
Graph Settings	
AutoScale	Yes
Show Lines	No
Show Data Points	Yes
Sweep	
Graph Display	Pressure vs Flow
Initial Delay (s)	5
Sample Period (ms)	1000
Sweep Both Pumps	No
Assign Pump 1 to Pre...	No
Start Voltage	24.000000
Cutoff Voltage	6.000000
Sweep Step (V)	1.000000
Auto Zero On Sweep	Yes
Auto Zero Delay (s)	2
Logging	
Log To File	Yes
Filename	Log1.csv
Date Format	DD MM YY

The flow meter:

The rate of flow can be measured in a number of ways. The diagram illustrates one - the turbine flow meter.

Two of these are provided in the kit and both come ready- calibrated, but for improved accuracy, these can be calibrated in situ for each experiment.



- Connect all hoses and ensure that there are no leaks
- Time how long it takes to pump one litre of water through the system. Hence derive the flow-rate in litres per minute.
- Compare this with the reading given by the 'Fluids' application.

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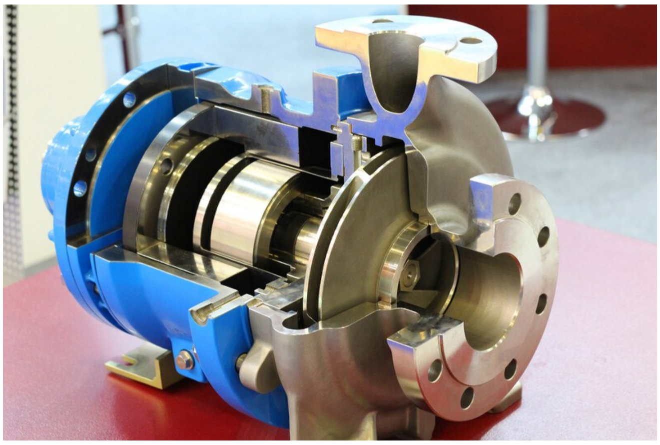
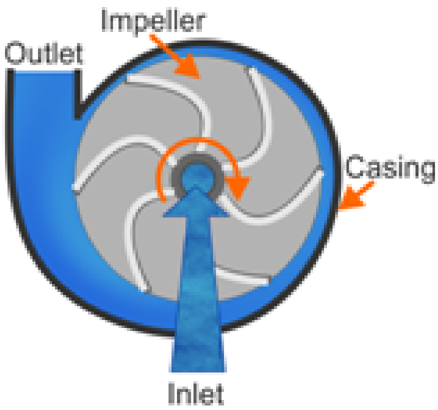
The pumps:

The workstation comes with two centrifugal pumps, driven by electric motors at a speed determined by the settings chosen on the 'Fluids' app.

The images below show:

- a photograph of a cutaway centrifugal pump;
- a schematic diagram of its structure.





Before they are used, the pumps must be 'primed' (filled with water.)

- Remove the pump module from the workstation and lower it below the level of water in the tank.
- Should any air locks remain, preventing the pump from priming fully, remove these by draining the system and repeating the procedure.

Once the pumps are running, check that there are no leaks!

- Remove air from the differential pressure sensor pipes by opening the bleed valves and filling the pipes and cavity with water until the sensor port is fully submerged

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Manometers:

The kit includes two types of manometer:

- traditional U-tube manometers, including an inclined U-tube manometer and a multitube manometer;
- differential pressure (solid state) manometers.

Generally speaking, use the multitube manometer for measuring low pressure and the differential pressure sensor for high pressures.

The kit uses two types of connection sockets:

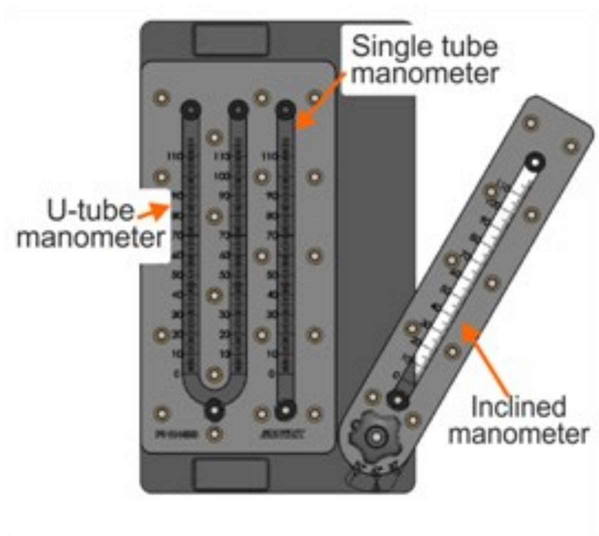
- normally open;
- self-sealing.

They can be distinguished by examining the shape of the body and release collar.

(As the name suggests, self-sealing sockets are closed and pressure-tight until pneumatic piping is inserted fully.)

Inclined manometer module:

This module contains three manometers - a single tube manometer, a U-tube manometer and an inclined single tube manometer. The angle of inclination of the latter can be adjusted, This allows the effects of the inclination to be investigated by comparing the reading with that on the single tube manometer.



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Multitube manometer (manual reading)

The multitube manometer, shown in the diagram, is basically an inverted U-tube manometer, but with three limbs.

This allows the user to compare the fluid pressure at three points in the fluid flow.

The common section, at the top, can be pressurised, using the pipette filler, to change the 'zero' pressure level for the three tubes.

All four pressure ports are sealed closed until a pneumatic connecting tube is inserted.

Differential pressure sensor (automated reading)

This has only two pressure ports, each leading to separate chambers.

A solid-state pressure sensor, located between the chambers isolates one from the other. When the chambers are at different pressures, a voltage signal is created by the sensor.

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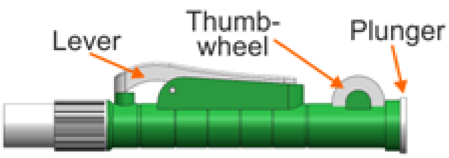
Setting up the manometers:

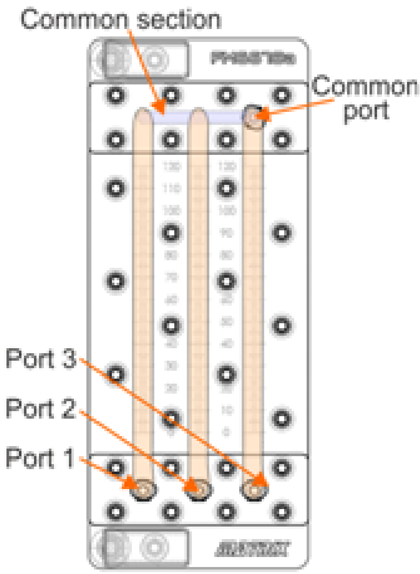
Before the multitube and differential pressure manometers are used, unwanted air must be purged from the connections.

Multitube manometer:

- Open the inlet valve on the front of the workstation.
- Open the 'Fluids Control' application, set the pump voltage to 12V (using either the slide bar control or 'Override') and switch it on.
  Running the pump in this way for a short time helps to remove air from the system.

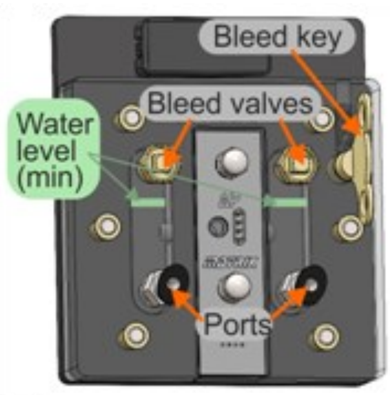
- Attach the pipette filler to the top (common) port of the manometer, with the plunger set about half way down its range. Remove air from the connecting tubing by lowering and then raising the pipette plunger slowly.
- Use the pipette filler thumbwheel to pressurise the section common to the three manometer tubes, until the water level in port 2 (centre) sits at 0mm.





Differential pressure sensor:

- The chambers are isolated from each other and must be adjusted separately.
- The level of water in each is regulated by using the 'bleed' key to open each bleed valve.
- In this way, fill the chambers to at least the level shown.



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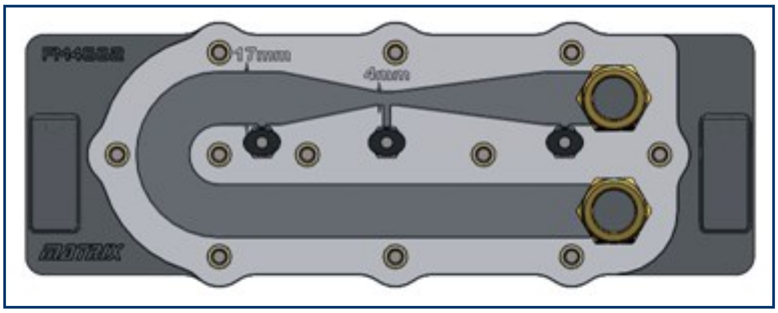
The Venturi tube module:

In this, the width of the flow-tube is reduced in one region, from 17mm to 4mm, as shown in the diagram.

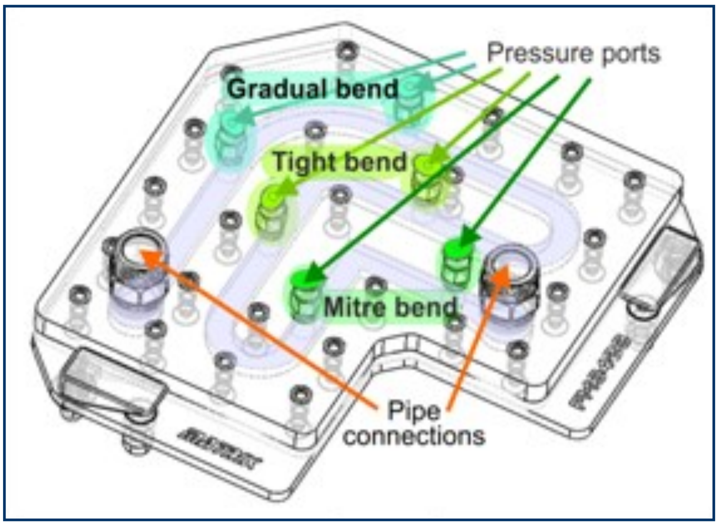


As a result, the fluid flows faster through this narrow region and there is a change in static pressure. This pressure change depends on the speed of flow of the fluid and is measured using one of the manometers.

There are three pressure ports in the module, allowing the user to monitor the drop in static pressure across the venturi and also to compare it with the pressure further downstream.

The 'Losses in bends' module:

The 'Losses in bends' module' contains three differently-shaped bends, shown below, each of which changes the flow direction by 90^0. It allows the user to measure pressure losses caused by the fluid flowing around bends.



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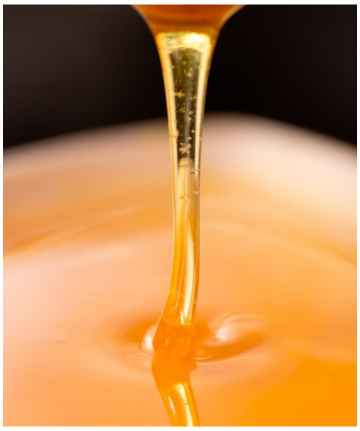
Worksheet 1
Viscosity matters

Viscosity measures a fluid's resistance to flow.
It is its 'gloopiness'.
It also indicates its effectiveness as a lubricant.

The surfaces of bearings in machinery are never completely smooth. When two bearing surfaces are in contact, these imperfections interfere, resulting in wear and in unwanted heating.

The role of a lubricant is to separate these surfaces to reduce those frictional forces.

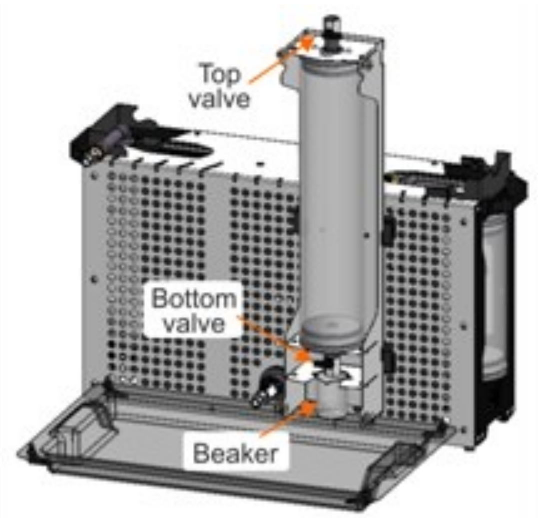


Over to you:

The diagram shows the viscosity apparatus attached to the workstation.

The kit includes the following ball-bearings:

- 2mm diameter (nominal) stainless steel;
- 3mm diameter (nominal) stainless steel;
- 4mm diameter (nominal) stainless steel;
- 5mm diameter (nominal) plastic ('Delrin');
- 6mm diameter (nominal) plastic ('Delrin').



- Set up the apparatus as shown.
- Open the top valve. Ensure that the bottom valve is fully closed.
- Using a funnel, fill the tube with vegetable glycerine.
- Close the top valve

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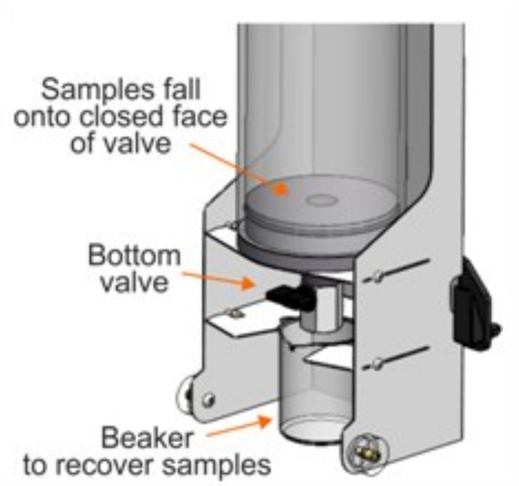
Over to you .....

- On the outside of the tube, stick a label so that its top edge is 400mm from the bottom of the tank to act as the 'start line'
- Open the top valve and insert first of these samples.
- Time how long it takes to fall from the 'start line' to the bottom of the tube.
- In the Student Handout, record the time taken and the distance travelled (400mm).
- Complete the calculations using these results and the formula given on the next page.
- Repeat this process for the other samples and then for the other types of ball-bearings.



To retrieve the ball-bearings:

- close both valves fully;
- tilt the tube slightly to move ball-bearings into the grey plastic end cap of the tube;
- place a beaker underneath the bottom valve;
- open the bottom valve briefly.

The samples should drop into the beaker (along with a small quantity of glycerine).

To recover the glycerine:

- fully open the bottom valve;
- slowly open the top valve - this controls over how quickly the glycerine drains from the tube.

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So what:

Provided that:

- the tube is wide enough so that its walls do not interfere with the falling ball-bearing;
- there is no turbulence caused by the falling ball-bearing;
- the viscosity is great enough that the ball-bearing achieves terminal speed almost immediately;

then the coefficient of dynamic viscosity η can be calculated from the formula:

$$\eta = \frac{2(\rho_s - \rho_g).g.R^2}{9V}$$

where ρ_s = density of the ball-bearing
ρ_g = density of glycerine
g = acceleration due to gravity
R = **radius** of the ball-bearing
V = terminal speed of the falling ball-bearing

The terminal speed of the ball-bearing

$$V = \frac{D}{t}$$

where **D** = distance fallen = 0.4m
t = time of flight.

- In the Student Handout:
  - use the formulae to calculate the coefficient of dynamic viscosity for glycerine;
  - compare your results with the official value for the viscosity for glycerine;
  - comment on this comparison, highlighting possible major sources of error.

Officially, the dynamic viscosity of glycerine is 1.5 Pa.s at 20^{0}C.
This value varies significantly with temperature and with water content.

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Worksheet 2

Calibrating the pressure gauge

Three types of pressure gauge are used in this module.

One, a solid state device, leads to a digital output.

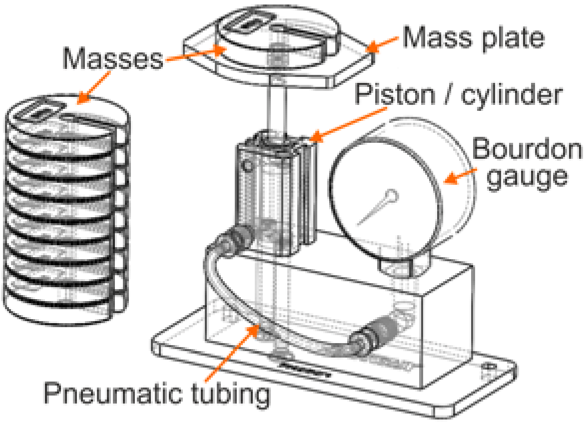
A second, a liquid-filled manometer, indicates pressure by the height of the liquid column.
The third, a Bourdon gauge, relies on the principle that excess pressure in a curved tube tends to straighten it.
Widely used in industry to measure fluid pressure, this gives an analogue reading.
This worksheet shows one way to calibrate it.

Overview:

The diagram shows the arrangement of the apparatus for this investigation.

The Bourdon gauge is connected via pneumatic tubing to the cylinder and the system is filled with water.

Weights added to the plate create known values of pressure which are then used to calibrate the gauge.



Over to you:

- The first task is to remove air from the system. To do so:
    - disconnect the pneumatic tubing from the Bourdon gauge port;
    - push the piston down as far as possible;
    - submerge the open end of the tubing in water;
    - pull the piston up as far as possible;
- Place a finger over the open end of the tubing and ***gently*** press down on the piston. If the result feels 'spongy', there is still some trapped air in the system.
  In this case, repeat this process.
  (Holding the cylinder upside down while pressing on the piston could help.)
- Once all air is removed, reattach the tubing to the Bourdon gauge port.

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Worksheet 2

Calibrating the pressure gauge

Over to you .....

- In the Student Handout table, record the gauge reading with no added weights. (When taking readings, lightly tap the gauge dial to remove the effect of friction.)
- Add one weight and record the resulting gauge reading.
- Continue in this way up to a maximum load of 1.5kg.
- Then remove the weights, one at a time and repeat the readings.
- Use these results and the formulae given below to complete the Student Handout table.
- On the axes provided in the Student Handout, plot the following graphs :
  - theoretical pressure against measured pressure (gauge reading) for increasing loads;
  - theoretical pressure against measured pressure for decreasing loads;
  - percentage error against measured pressure for both increasing and decreasing loads.

So what?

- Determine the gradient of the first graph. It can be used as a correction factor for the readings shown on the Bourdon gauge.
- In the Student Handout, comment on the significance of the shape of the percentage error against measured pressure graph.

Some formulae:

Theoretical value of pressure, **P**, exerted by the weights, is given by:

$$P = \frac{F}{A} = \frac{m.g}{\pi.r^2}$$

where **F** = force exerted by the weights;
m = mass added in kg;
g = gravitational field strength = 9.81 $N.kg^{-1}$;
A = area of piston = $\pi \times r^2$;
r = radius of piston = 6mm = 6×10^{-3}m.

P will be in pascals (Pa) when **F** is in newtons (N) and **A** is in metres^2 (m^2).

$$Percentage\ error = \frac{gauge\ reading - theoretical\ pressure}{theoretical\ pressure} \times 100\%$$

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Worksheet 3
Using liquid-filled manometers

Chronologically, this type of manometer came first, invented in the 17th century.

A common application is the sphygmomanometer, shown on the left, used to measure blood pressure.

The cuff, placed around the patient's arm is inflated until the pressure of the air in it equals blood pressure.

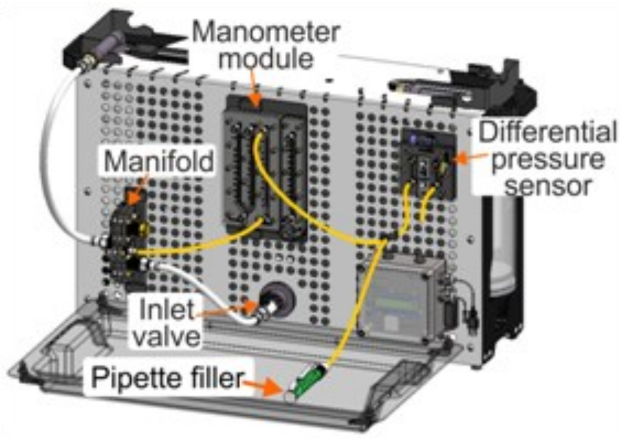
This air pressure, and hence blood pressure, is indicated by the height of the mercury column in the tube.

Single-limb manometer

Overview:

The diagram shows the apparatus set up to investigate the single-limb manometer.

Using this, the pressure reading shown on the manometer can be compared to that given by the differential pressure sensor.



Over to you:

- Setup the apparatus as shown.
- Open the inlet valve to allow water flow around the system.
- Press the lever on the pipette filler to open the manometer and pressure sensor to atmospheric pressure.
  The water level in the manometer will rise to match that in the main water tank.
- Press the pipette filler plunger (or use the scroll wheel) to adjust the water level in the manometer until it is exactly on the zero line.
- Open the 'Fluids' application and press 'Go' to initiate communication between it and the differential pressure sensor.
- Use the app. to 'zero' the differential pressure sensor.
  Both pressure instruments now agree about zero pressure.
- Retract the plunger of the pipette filler until the water column has a height of 10mm.
- In the table in the Student Handout, record the corresponding pressure reading shown by the differential pressure gauge.
- Repeat this process until the water column reaches a height of 100mm.

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So what?

The pressure, **P**, at the base of the water column in the single-limb manometer is given by:

$$P = \rho . g . h$$

where ρ = density of water = 1000kg.m^{-3}
g = gravitational field strength = 9.81N.kg^{-1}
h = height of water column in m.

- Use this formula to calculate the pressure at the base of the water column, taking care to convert the column height to metres.
- Complete the second column of the table.

The percentage error in the reading of the differential pressure sensor is given by:

$$Percentage\ error = \frac{Sensor\ reading - theoretical\ pressure}{theoretical\ pressure} \times 100\%$$

- Hence calculate the percentage error of the differential pressure sensor.
- Complete the fourth column of the table.
- What do these results show about the performance of the differential pressure sensor compared to that of the single-limb manometer?
  Write your comments in the Student Handout.

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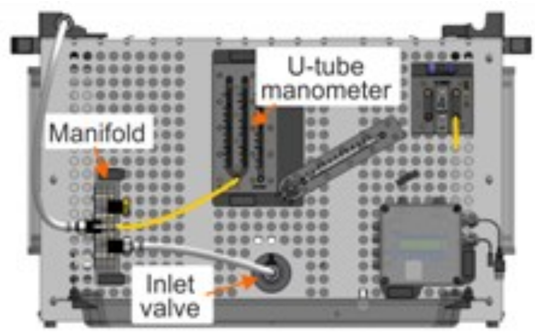
U-tube manometer

Initial setup:



- Attach the 4mm tubing as shown opposite.

  (The inclined manometer is tilted to make the diagram clearer. It plays no part in this investigation.)
- Allow the water level in the manometer to match that in the workstation tanks.
- Try to get the water level in both limbs to reach the 60mm mark on the vertical scale by adjusting the height at which the manometer module is clamped to the workstation or by changing the liquid level in the main tank.
- When the water level reads 60mm in both limbs, remove the 4mm tubing from the U-tube manometer and then remove it from the manifold, to prevent leaks.

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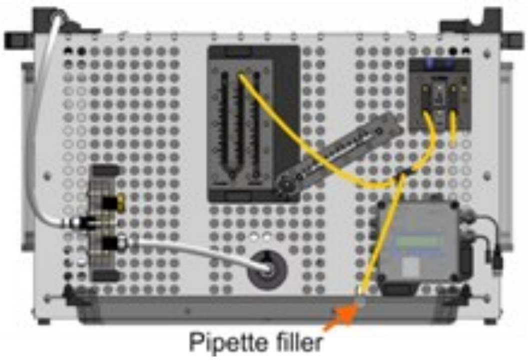
U-tube manometer .....

Over to you:

- Modify the setup as shown opposite.
- Use the pipette filler to equalize the water level in the two limbs of the manometer. If necessary, adjust it to 60mm, as described earlier.
- In the Student Handout, record the initial water levels for the left-hand and right-hand limbs
- Use the 'Fluids' app. to 'zero' the differential pressure sensor.



- Press the plunger of the pipette filler until there is a 10mm height difference in the water columns in the two limbs of the manometer.
- In the table in the Student Handout, record the corresponding pressure reading shown by the differential pressure gauge.
- Repeat this process until the difference in the height of the water columns reaches 100mm. Complete the third column of the table, the height difference.

So what?

The applied pressure, **P** is given by:

$$P = \rho . g . h$$

where ρ = density of water = 1000kg.m^{-3}
g = gravitational field strength = 9.81N.kg^{-1}
h = height of water column in m.

- Use this formula to complete the fourth column of the table, the calculated value of pressure, indicated by the manometer.
- Use these results to complete the sixth column, the percentage error of the differential pressure sensor, using the formula:

$$Percentage\ error = \frac{Sensor\ reading - theoretical\ pressure}{theoretical\ pressure} \times 100\%$$

- What do these results show about the performance of the differential pressure sensor compared to that of the single-limb manometer?
Write your comments in the Student Handout.

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Worksheet 4
Inclined manometers

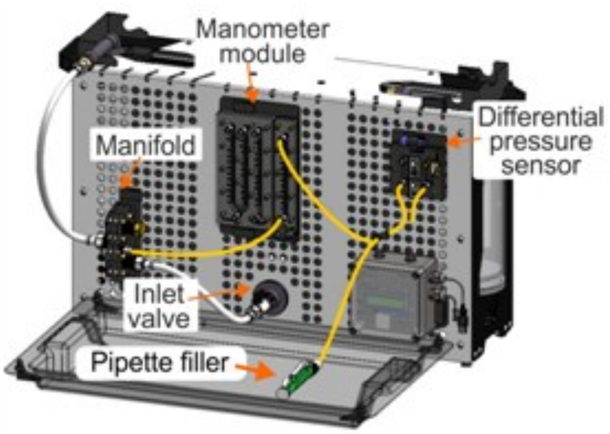
Sometimes, the requirement is for sensitivity - where a small change in pressure causes an appreciable change in the reading.

An example is in air-conditioning systems, where, as the air filter clogs up with dust, the pressure difference across it increases.

Monitoring that pressure difference can warn when the filter needs changing or cleaning.

Overview:

The diagram shows the apparatus set up to investigate the inclined manometer in the vertical (0^0) position.



Again, the manometer pressure reading will be compared to that given by the differential pressure sensor. The experiment is then repeated with the manometer inclined at angles of 60^0 and then 30^0.

Over to you:

- Setup the apparatus as shown.
- Open the inlet valve so that water can flow.
- Press the pipette filler lever to open manometer and pressure sensor to atmospheric pressure.
- Use the pipette filler to set the water level in the manometer on the zero line.
- Open the ‘Fluids’ application and press ‘Go’ to initiate communications.
- Use the app. to ‘zero’ the differential pressure sensor, so that both instruments agree about zero pressure.

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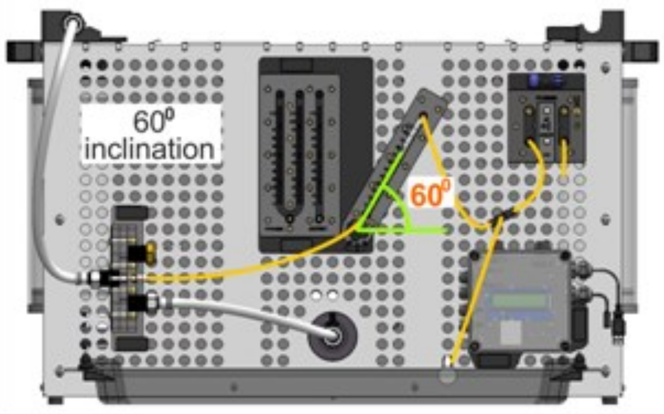
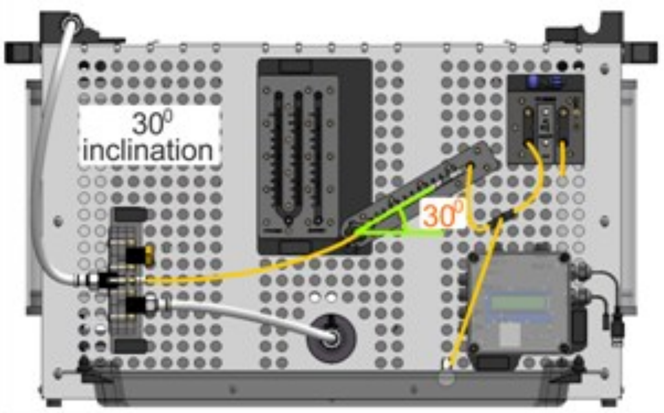
Over to you .....

- Retract the plunger of the pipette filler until the water column has a height of 10mm.
- In the ‘90^0’ column in the Student Handout table, record the corresponding differential pressure gauge reading .
- Repeat this process until the height of the water in the manometer limb reaches 100mm and hence complete the table.

- Now, tilt the inclined manometer to the 60° position, shown in the next diagram.
- Repeat the procedure and record the results in the ‘60^0’ column in the Student Handout table.



- Finally, tilt the inclined manometer to the 30° position, shown in the diagram below.
- Repeat the same procedure and record the results in the ‘30^0’ column in the Student Handout table.



- What do these results show about the performance of the inclined manometer compared to the other manometers?
  Write your comments in the Student Handout.

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Worksheet 5

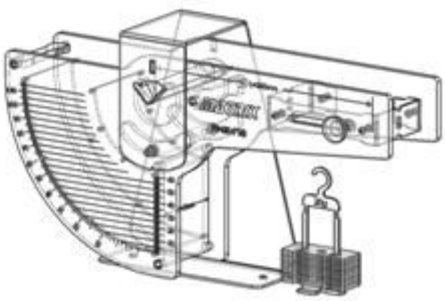
Centre of pressure

Gravity attracts every particle in the Universe to every other particle. Complicated!!!!
To simplify it, we use the idea of *centre of gravity*, the point where all these forces seem to act.

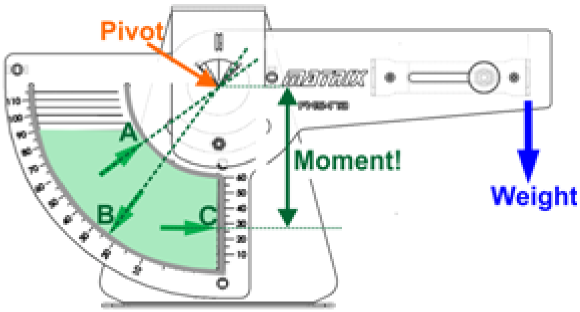
Similarly, fluids exert pressure on every part of a surface but we treat it as if they acted at a single point, called the centre of pressure.
This simplifies the design of a host of items, from dams and yachts to aeroplane wings.

Overview:

The equipment is shown in the diagrams below.



A water tank is pivoted at the centre of a frame.
Weights are added to balance out the effect of the water pressure on the end of the tank.



Forces caused by a fluid always act at right-angles to a surface.
The shape of the tank ensures that forces on the curved surfaces, such as those at **A** and **B**, exert no moment (turning effect,) about the pivot.

Only forces acting on the end plate, such as those at **C**, exert a moment about the pivot.
By balancing this moment against that produced by a known weight at a known distance from the pivot, the centre of pressure can be determined.

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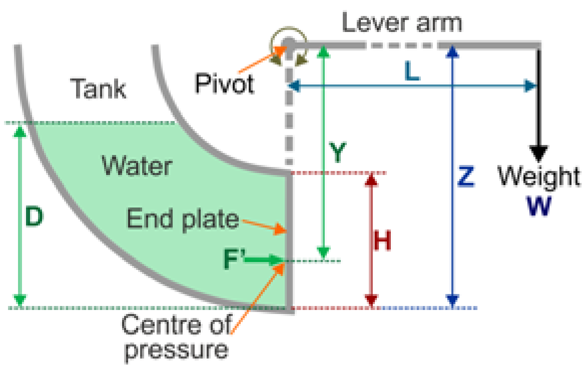
Over to you:

- Balance the empty the 'Centre of pressure' tank on the knife-edge pivot.
- Use the sliding counterweight to balance it so that the end plate of the tank is vertical.
- Measure:
    - the height **Z** of the pivot above the base of the tank;
    - the length **L** of the lever arm;
    - the width **B** of the end plate;
    - the height **H** of the end plate.



- Record these measurements in the Student Handout.
- Hang the empty mass hanger (20g) from the end of the balance arm.
- Slowly add water to the tank until the end plate of the tank is vertical again.
- Measure the depth of water, **D**, in the tank.
- Record it in the table in the Student Handout.
- In the fourth column, add the letter '***P***' if the end plate is only partly submerged or '***F***' if it is fully submerged.
- Place a 5g mass on the mass hanger.
- Add more water until the end plate of the tank is vertical again.
- Measure the new depth of water in the tank.
- Record it in the Student Handout table and add the letter '***P***' or '***F***' in the fourth column each time.
- Repeat this procedure, adding 5g masses to the mass hanger and balancing it with added until the tank is full.

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So what:

Water pressure in the tank increases with depth and so the pressure on the lower half of the end plate is greater than that on the upper half.

As a result, the centre of pressure is not at the centre of gravity but below it.

Since pressure increases linearly with depth, pressure **P'** at the centre of pressure is the average of the pressure $\mathbf{P_{top}}$ at the top of the end plate and $\mathbf{P_{bottom}}$ at the bottom.

In other words,

$$P' = \frac{(P_{top} + P_{bottom})}{2}$$

The force exerted on the end plate at the centre of pressure **F' = P' . A** where **A** = area of end plate under water.

$$F' = \frac{(P_{top} + P_{bottom})}{2} \cdot A$$

Hence (In this treatment, we ignore atmospheric pressure which acts equally on all surfaces.)

This force exerts a moment (**F'.Y**) about the pivot, where **Y** = vertical distance from centre of pressure to pivot.

When the pivot arm is balanced by weight **W** (in Newtons) at distance **L** from the pivot, then from the principle of moments,

$$W \cdot L = F' \cdot Y$$

giving

$$Y = \frac{W \cdot L}{F'} = W \cdot L \cdot \left(\frac{2}{P_{top} + P_{bottom}}\right)$$

The area of the end plate under water, **A**, depends on whether the end plate is fully submerged or not.

The depth of water also affects the pressures $\mathbf{P_{top}}$ and $\mathbf{P_{bottom}}$.

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Worksheet 5
Centre of pressure

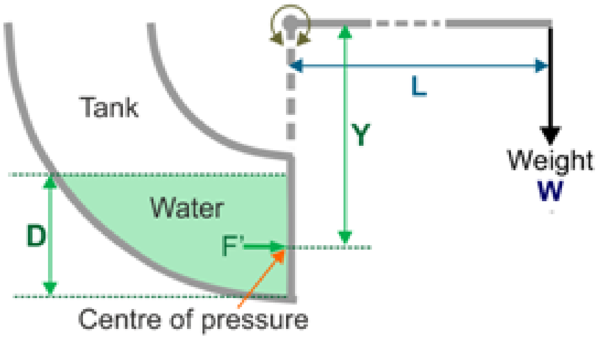
So what .....

When the end plate is only partially submerged:

Area of end plate under water = **B** . **D**

where **B** = width of end plate in m

D = depth of water in m



Then:

P_{top} = 0 (in excess of atmospheric pressure)

P_{bottom} = **D** . ρ . **g**

where ρ = density of water = 1000kg.m^{-3}

g = gravitational field strength = 9.81 N.kg^{-1}

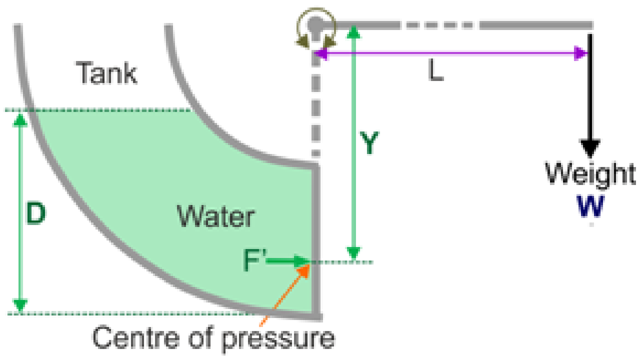
Hence $$Y = \frac{2}{\left((0+D)\cdot\rho_{Water}\cdot g\right)\cdot B\cdot D}\cdot W\cdot L = \frac{2}{D^2\cdot\rho_{Water}\cdot g\cdot B}\cdot W\cdot L \qquad \textbf{(1)}$$

When the end plate is fully submerged:

Area of end plate under water = **B** . **H**

where **B** = width of end plate,

H = height of end plate



Then:

P_{top} = (**D** - **H**) . ρ . **g**

P_{bottom} = **D** . ρ. **g**

Hence

$$Y = \frac{2}{(D-H)\cdot\rho_{Water}\cdot g + D\cdot\rho_{Water}\cdot g)\cdot B\cdot H}\cdot W\cdot L$$

$$Y = \frac{2}{\left((2\cdot D)-H\right)\cdot\rho_{water}\cdot g\cdot B\cdot H}W\cdot L \qquad \textbf{(2)}$$

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So what .....

- Use the appropriate formula (**1** or **2**), depending on whether the end plate is totally submerged or not, to calculate the distance **Y** to the centre of pressure for each depth reading.
- Using the axes provided in the Student Handout, use your results to plot a graph of the force **F'** exerted on the end plate vs depth **D** of water.

It can be shown that:

When the end plate is partially submerged:

$$Y = Z - \left(\frac{D}{3}\right)$$

When the end plate is fully submerged:

$$Y = \frac{\left(\frac{H^2}{12} + \left(D - \frac{H}{2}\right)^2\right)}{D - \frac{H}{2}} + Z - d$$

- On the axes provided, use these formulae to plot graphs of :
  - the theoretical value of **Y** vs depth **D** of water;
  - the theoretical value of **Y** vs experimental value of **Y**.

- In the Student Handout:
  - comment on the shape of the first two graphs and what happens when the end plate becomes fully submerged;
  - comment on discrepancies between the experimental and theoretical values for the location of the centre of pressure.

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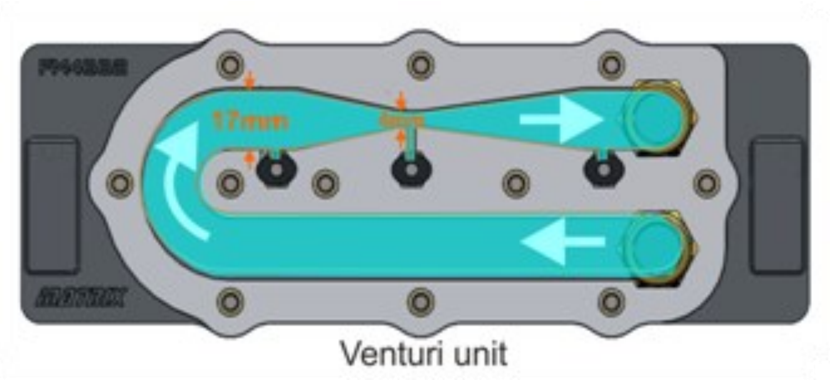
Worksheet 6

Bernoulli's principle

It starts with the conservation of energy - that the sum of all forms of energy is constant in the fluid.

When the speed of a fluid increases, its kinetic energy increases. To conserve total energy, there must be a decrease in potential or internal energy.

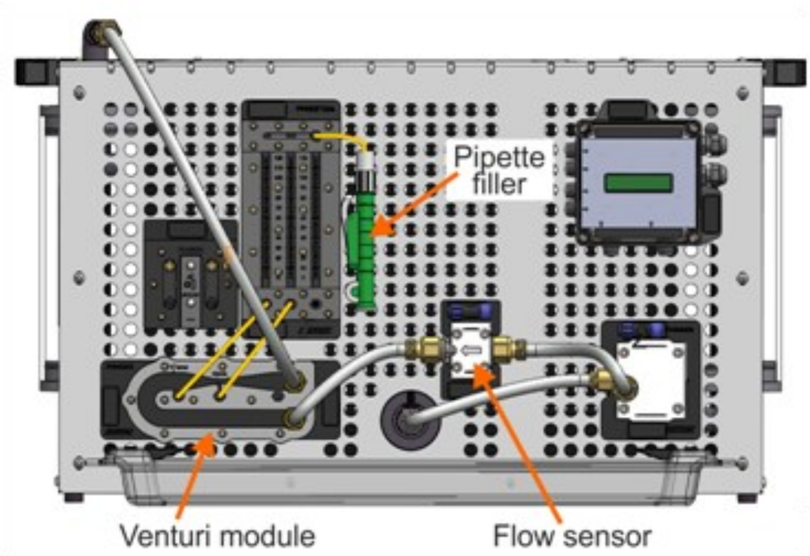
This investigation focuses on the Venturi tube module. As shown, the venturi is formed where the width of the flow-tube reduces from 17mm to 4mm.



Over to you:

1. Using the multitube manometer:

- Set up the equipment as shown in the diagram:



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Over to you: .....

- Prepare the manometer unit and prime the pump as described in the introduction.
- Use the 'Fluids' app. 'Override' button to set the pump voltage to 18V and switch on the pump.
- Check that there are no leaks.
- In the table in the Student Handout, record the height difference of the water columns in the limbs of the multitube manometer (**in metres**) and the flow-rate (from the turbine sensor.)
- Lower the pump voltage to 17V, to reduce flow-rate and note the height difference again.
- Continue in this way until the pump voltage is 6V.

So what:

- For each value of height difference, calculate the corresponding pressure difference between the two water columns using the formula:

$$\Delta P = (h_2 - h_1) \cdot \rho \cdot g$$

where **ΔP** = pressure difference in Pa,

(h_2 - h_1) = height difference **in m**,

ρ = density of water = 1000 kg.m^{-3} (though this varies with temperature,)

g = gravitational field strength = 9.81 N.kg^{-1}

- Use the axes provided in the Student Handout to plot a graph of measured pressure against flow-rate.

Challenge 1:

- Connect right hand port of the Venturi module to port 3 of the multitube manometer.
- For a range of pump voltages, compare the water levels in the left and right-hand tubes of the manometer.
- Why is there a head loss along the straight section of the flow-tube?
  Suggest reasons in the Student Handout.

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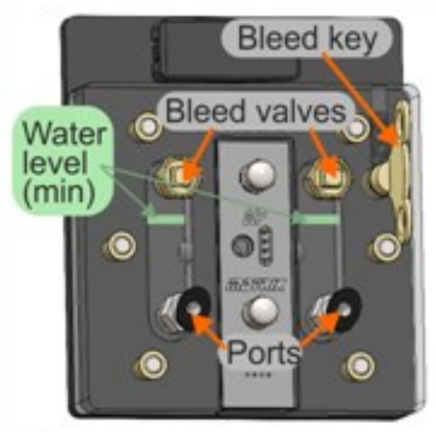
Over to you: .....

2. Using the differential pressure sensor:

- Disconnect the Venturi module from the multitube manometer.
- Connect the pressure ports either side of the venturi to the ports of the differential pressure sensor instead.
- Prepare the manometer as described in the introduction.



- Open the 'Fluids' application.
- With the pumps switched off, 'zero' pressure sensor 1.
- Set the application properties as shown opposite.
- Click on the 'Sweep' button above 'Pump 1'.
- Check that there are no leaks.

As specified in the app. Properties, the pump begins at the 'Start Voltage' and then ramps down in steps specified in the 'Sweep Step' field, until it reaches the 'Cutoff Voltage'. It takes and records pressure and flow-rate readings as it does so.

The application creates a graph of pressure vs flow-rate on screen, as measurements are taken.

- Obtain a copy of the readings by clicking on the 'Log Stats' button.
- Import these into a spreadsheet and use them to obtain a graph of measured pressure against flow-rate.

Properties	
Comms Method	USB (COM)
COM Port Settings	
Autodetect	Yes
COM Port	
Graph Settings	
AutoScale	Yes
Show Lines	No
Show Data Points	Yes
Sweep	
Graph Display	Flow vs Pressure
Initial Delay (s)	5
Sample Period (ms)	500
Sweep Both Pumps	No
Assign Pump 1 to Pre...	No
Start Voltage	24.000000
Cutoff Voltage	6.000000
Sweep Step (V)	0.250000
Auto Zero On Sweep	Yes
Auto Zero Delay (s)	2
Logging	
Log To File	Yes
Filename	Log1.csv
Date Format	DD MM YY

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So what:

Theoretical flow-rate for a given pressure difference:

Bernoulli's principle leads to the following equation:

$$P_1 + \frac{1}{2}(\rho \cdot v_1^2) + \rho \cdot g \cdot h_1 = constant$$

where **p** is the static pressure exerted by a fluid, of density ρ, travelling at speed **v** at a height **h** above some reference level.

Putting this another way, looking at two points, **1** and **2**, in the fluid stream:

$$P_1 + \frac{1}{2}(\rho \cdot v_1^2) + \rho \cdot g \cdot h_1 = P_2 + \frac{1}{2}(\rho \cdot v_2^2) + \rho \cdot g \cdot h_2$$

Assuming a horizontal flow, i.e. $\mathbf{h_1} = \mathbf{h_2}$, this equation becomes:

$$P_1 + \frac{1}{2}(\rho \cdot v_1^2) = P_2 + \frac{1}{2}(\rho \cdot v_2^2)$$

or, pressure difference,

$$\Delta P = P_1 - P_2 = \frac{1}{2}(\rho \cdot v_2^2) - \frac{1}{2}(\rho \cdot v_1^2)$$

Now, Volume flow-rate $Q = v \cdot A$

where **A** is the cross-sectional area of the pipe,
v is the fluid velocity

or

$$v = \frac{Q}{A}$$

The flow-rate is constant throughout the venturi - a consequence of the conservation of mass. When the area **A** decreases, the speed of the fluid increases etc.

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Hence: $$v_1 = \frac{Q}{A_1}$$

and $$v_2 = \frac{Q}{A_2}$$

Substituting these values into the equation for pressure difference Δ**p**:

$$\Delta P = \frac{1}{2}\left(\rho \cdot \left(\frac{Q}{A_2}\right)^2\right) - \frac{1}{2} \cdot \left(\rho \cdot \left(\frac{Q}{A_1}\right)^2\right)$$

or $$\Delta P = \frac{\rho \cdot Q^2}{2} \cdot \left(\left(\frac{1}{A_2}\right)^2 - \left(\frac{1}{A_1}\right)^2\right)$$

$$Q = \sqrt{\frac{2 \cdot \Delta P}{\rho \cdot \frac{1}{A_2^2} - \frac{1}{A_1^2}}}$$

This equation predicts that flow-rate and pressure difference are not directly proportional.

So what .....

- On the graph of measured pressure versus flow-rate, add a second graph showing theoretical pressure difference, Δ**p**, versus flow-rate, **q**, and compare the graphs.
- Comment on the comparison in the Student Handout.

Challenge 2:

In practice, not all of the potential energy stored in the fluid converts into kinetic energy as it flows through the venturi, because of frictional effects. How efficiently this conversion takes place depends on the geometry and other physical characteristics of the nozzle.
A measure of this efficiency is given by the *coefficient of discharge*, $\mathbf{C_d}$, for the venturi.
Coefficient of discharge for a nozzle or other constrictions is defined as the ratio of actual discharge to the theoretical discharge.

Try different values of $\mathbf{C_d}$, between 0 and 1, in the formula for the theoretical pressure difference to find the best match to model the behaviour of the apparatus.

Describe your approach and findings in the Student Handout.

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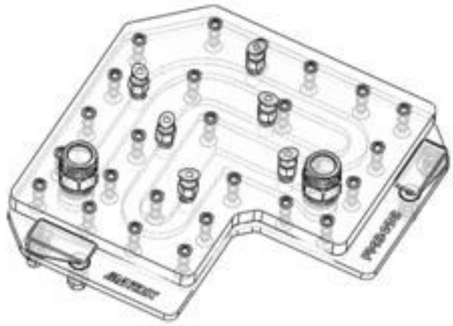
Worksheet 7
Minor losses in bends

Fluids have mass and so have momentum when they move. As a result, they try to continue flowing in a straight line and extra forces must be involved to make them turn a corner.
At a bend, fluid at the centre of the flow moves towards the outer edge of the bend creating a pressure drop and energy loss across the flow.

Overview

This investigation focuses on flow in the 'Losses in bends' module'.

This contains three differently-shaped bends, shown opposite, each of which changes the flow direction by 90^0.

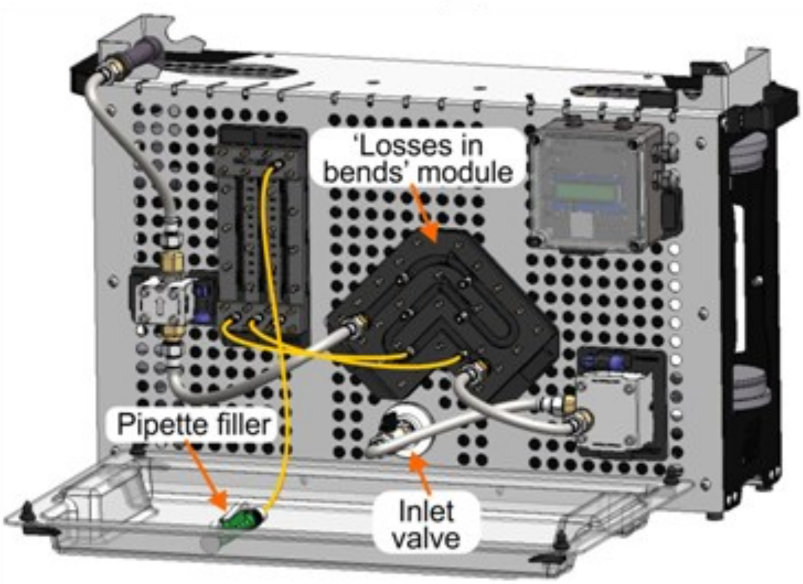


Over to you:

Initial set-up:

- The diagram below shows the equipment set up to investigate flow through the mitre bend. Set it up as shown.

(Connections to the data control module are not shown to make the diagram clearer.)



- Prime the pump as described in the introduction.
- Using the 'Fluids' app. 'Override' button, set the pump voltage to 18V and switch on.
- Check that there are no leaks.

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Over to you .....

- In the table in the Student Handout, record:
  - the height difference (**in metres**) of the water columns in the limbs of the multitube manometer;
  - the flow-rate shown on the 'Fluids Control' application.
- Repeat this for pump voltages of 14V, 10V and 6V and complete the first section of the table with your results.
- Connect the manometer to the pressure ports on the '**tight**' bend and repeat this process, recording your results in the centre section of the table.
- Finally, repeat the process again using the '**gradual**' bend and record the results.

So what:

- First, use the flow-rate, **q**, to calculate the flow-speed, **v**, using the continuity of mass formula, seen earlier:

flow-rate **q** = **v** x **A** where **A** is the cross-sectional area of the pipe,

Hence
$$v = \frac{Q}{A}$$

- Complete the remaining tables in the Student Handout with your results.

The pressure ('head') loss, H_{loss}, caused by a fitting such as a bend is found to be proportional to the square of the flow-speed **v**.

This leads to the equation:

$$H_{loss} = Constant \cdot \frac{v^2}{2 \cdot g}$$

where g = acceleration due to gravity = 9.81m.s^{-2}

This constant is known as K_{loss}, the loss coefficient of the bend.

Rearranging the equation:

$$K_{loss} = \frac{H_{loss} \cdot 2 \cdot g}{v^2}$$

- Use this formula to calculate values of K_{loss} for each value of flow-speed for each type of bend.
- Record your results in the tables provided in the Student Handout.

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Worksheet 8
Centrifugal pump

Pumps have been around for centuries - irrigating fields, draining bogs, providing water for domestic use etc.

Motive power to drive the pump came originally from a wind turbine, later from a steam engine and today from an internal combustion engine or an electric motor.

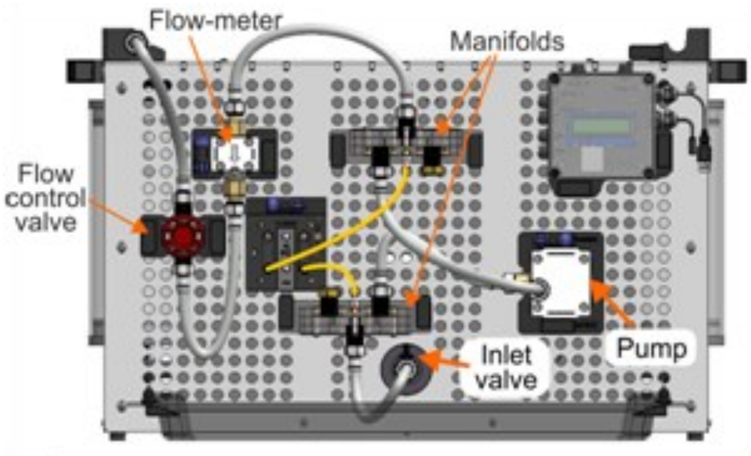
The big advantage of the centrifugal pump, invented in the 17th century, is its simplicity having only two main parts - the casing and the impeller - no valves!

Over to you:

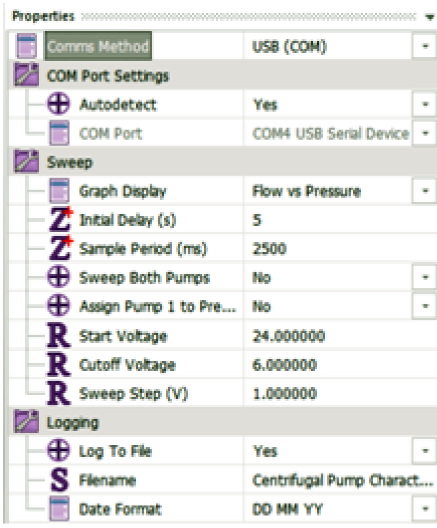
Initial set-up:

- The diagram shows the set up for the investigation.

(The data control module connections are not shown to make other connections clearer.)



- Prime the pump.
- Set up the equipment as shown.
- Open the inlet valve and flow-control valve and check for leaks.
- Bleed air from the pressure sensor and connecting pipes until the sensor is submerged.
- Set the 'Fluids' application properties as shown in the dialogue box opposite.



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Worksheet 8

Centrifugal pump

Over to you .....

- Close the flow-control valve to stop the circulation of water round the system.
- Click ‘Override’ for pump 1 and set the voltage to 24V.
- Click ‘Sweep’. The software now sweeps through the voltage range specified in the Properties panel, collecting sensor values as it does so.
- The software displays a graph of flow-rate vs pressure. Take a screen shot and crop it to obtain an image of this graph. Label it “Flow-rate 0”.
- Slowly open the flow-control valve until the flow-rate reaches 1 $l.min^{-1}$.
- Click ‘Sweep’ and store the resulting graph, as “Flow-rate 1 $l.min^{-1}$”.
- Repeat this procedure for a flow-rate of 1.5 $l.min^{-1}$, labelling the graph appropriately.
- Increase the flow-rate in steps of 0.5 $l.min^{-1}$, activating ‘Sweep’ to obtain flow-rate vs pressure graphs each time.
- Repeat this procedure until the flow-control valve is fully open.

- In the Student Handout, comment on any deductions you can draw from the sequence of graphs.

Challenge:

Investigate the variation of pump efficiency with flow-rate for a pump voltage of 24V.

$$Efficiency = \frac{Useful\ Power\ out}{Power\ in} \times 100\%$$

$$Pump\ efficiency = \eta_{Pump} = \frac{Water\ power\ delivered\ by\ the\ pump}{Electrical\ power\ supplied\ to\ the\ pump} \times 100\%$$

Important: This formula needs the quantities expressed in the following units:
pressure - in Pa (i.e. $N.m^{-2}$)’
volume flow-rate in $m^3.s^{-1}$

$$Water\ power\ delivered\ by\ the\ pump = Pump\ Pressure\ \times Volume\ flow\ rate$$

$$Electrical\ power\ supplied = Pump\ voltage\ \times Pump\ current$$

Use the data obtained in the investigation to plot a graph of efficiency vs flow-rate for a pump voltage of 24V.

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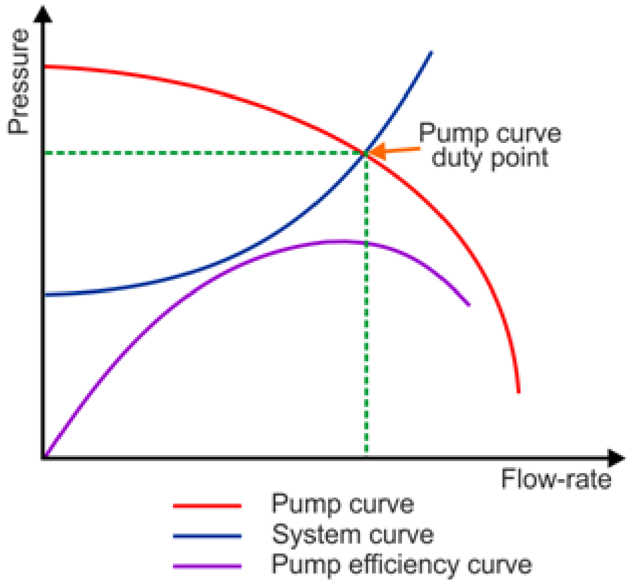
So what:

The performance of a pump is usually described by the **pump curve**, a graph showing the relationship between the pressure and flow-rate delivered by the pump.

A typical pump performance curve is shown in the graph opposite, along with related curves.



System curve:

A number of loss mechanisms arise when a fluid flows through a system, including friction between the fluid and the walls of the pipes, friction between adjacent particles in the fluid, friction in the piping components such as bends and connectors in the system, and increase in the elevation of the fluid.

These mechanisms depend on factors such as pipe length and diameter, the viscosity and temperature of the fluid and the number and type of pipe fittings in the flow path.

The system curve represents the total effect of these loss mechanisms, expressed as the pump pressure, (head,) required to deliver a particular flow-rate of fluid against these losses.

The point at which the system curve and pump curve intersect is known as the 'duty point'. A centrifugal pump always operates at this point, when the pressure it delivers matches the resistance of the system.

Pump efficiency curve:

Efficiency of a pump is the ratio of the output (water) power to the input (shaft) power expressed as a percentage. It depends on factors such as turbulence and impeller size, (compared to the casing) and shape.

Pumps use less energy when operating at higher levels of efficiency. The BEP (best efficiency point) is the point on a pump curve of most efficient operation. When the flow-rate is zero, efficiency is zero. As the flow increases so does efficiency, until the flow through the pump becomes more turbulent. At that point, efficiency starts to drop. Somewhere between these conditions, there is a flow-rate at which efficiency is a maximum. This is the BEP.

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Worksheet 9

Pumps in series and in parallel

In electric circuits, batteries are often connected in series, to increase the voltage, or in parallel, to increase the current.

In the same way, several pumps can be connected in series or in parallel to increase fluid pressure or flow-rate.

Over to you:

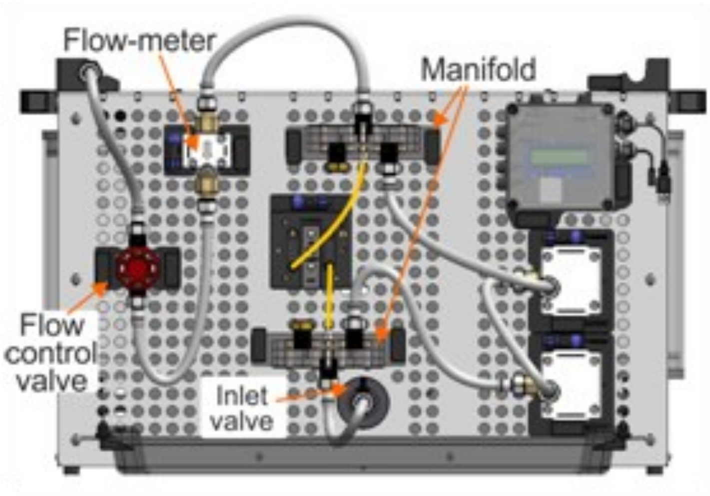
Pumps in series:

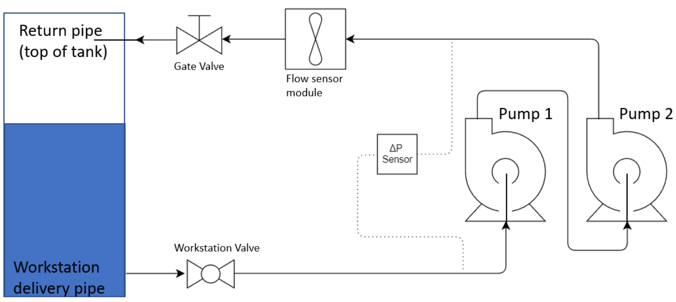
The diagrams show the arrangement used to investigate the performance of two pumps connected in series.

(The data control module connections are not shown to make other connections clearer.)

- Connect the modules as shown.

  Notice that the pumps are connected in series, one after the other.
- Ensure that hoses are hand-tight and correctly aligned.
- Open the inlet valve and flow-control valve.
- Purge air from the system by running both pumps (using the 'Fluids' application) and closing then re-opening the inlet valve a few times. As you do so, check for leaks in the system.
- Turn off the pumps.
- Connect the 4mm tubing to the differential pressure sensor, as shown (in yellow).
- Bleed air from the pressure sensor module until the sensor is submerged.



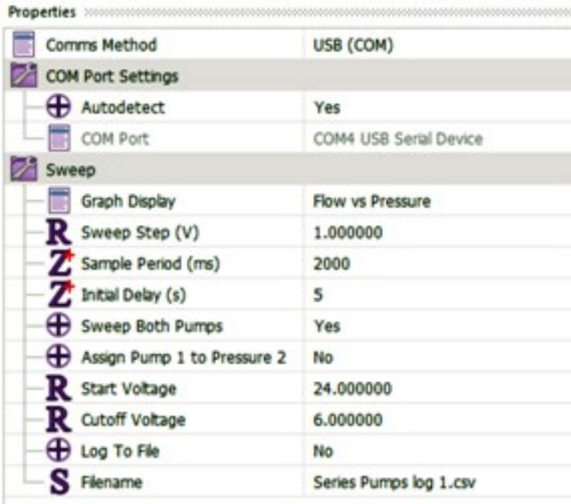


Worksheet 9

Pumps in series and in parallel

Over to you .....

- Open the inlet valve fully.
- With the pumps switched off, ‘zero’ pressure sensor 1.
- Fully close the flow-control valve.



- Open the ‘Fluids’ application.
- Enter the ‘Sweep’ settings shown opposite in the Properties panel.
- Fully close the flow-control valve, click on ‘Sweep’ and wait for the sweep sequence to complete. Take a screen shot and crop it to obtain an image of this graph. Label it “Pump churning”.
- Open the inlet valve.
- Click ‘Override’ for pump 1, set the voltage to 24V and switch on the pump.
- Do exactly the same thing for pump 2.
- Slowly open the flow-control valve until the flow-rate reaches 1 $l.min^{-1}$.
- Click ‘Sweep’.
  The software now sweeps through the voltage range specified in the ‘Properties’ panel, collecting sensor values as it does so.
- The software displays a graph of flow-rate vs pressure. Take another screen shot and label the image “Flow-rate1 $l.min^{-1}$”.
- Repeat this procedure for a flow-rate of 1.5 $l.min^{-1}$.
- Continue in this way, increasing the flow-rate in steps of 0.5$l.min^{-1}$ until the flow-control valve is fully open.

  (The log file inserts a distinguishing header between the sweep sequences.)

- In the Student Handout, comment on any deductions you can draw from the sequence of graphs.

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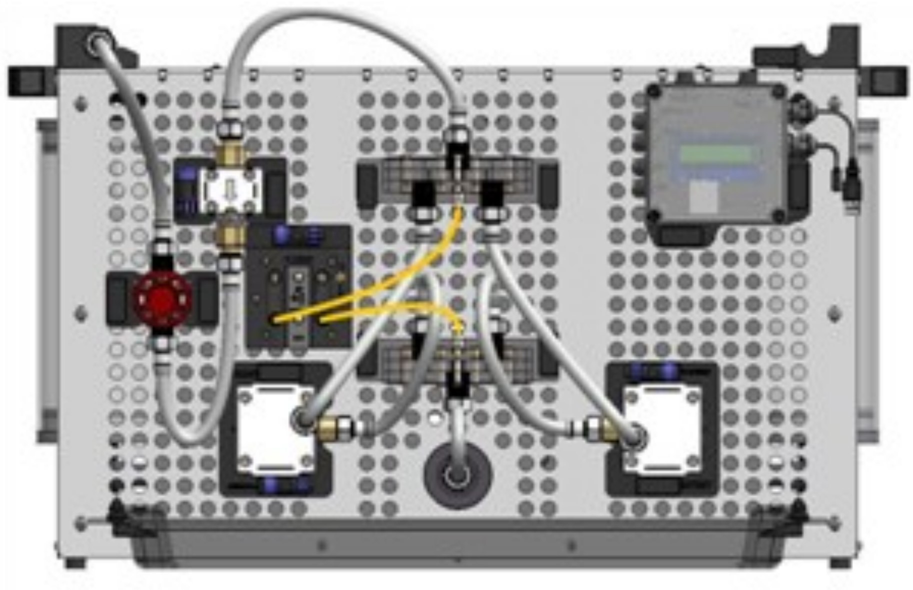
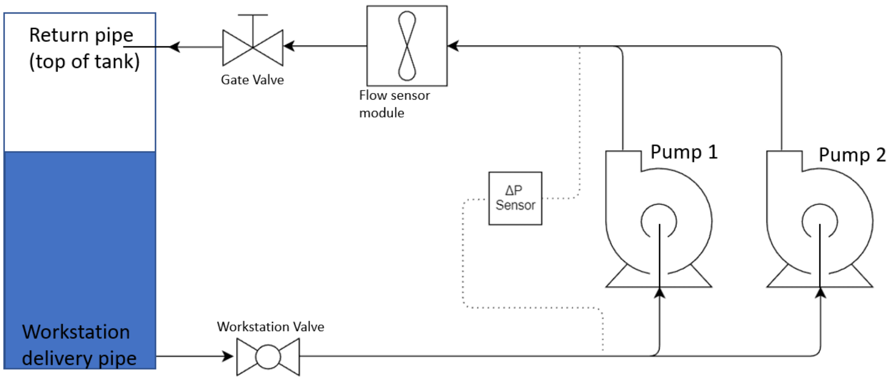
Pumps in parallel:

The next diagrams show the arrangement used to test f two pumps connected in parallel. (As usual, the data control module connections are not shown to simplify the diagram.)





Challenge:

- Carry out a similar investigation to the one on series pumps to obtain a series of graphs showing the performance of the pump combination over a range of flow-rates.
- Again, in the Student Handout, comment on any deductions you can draw from the sequence of graphs.

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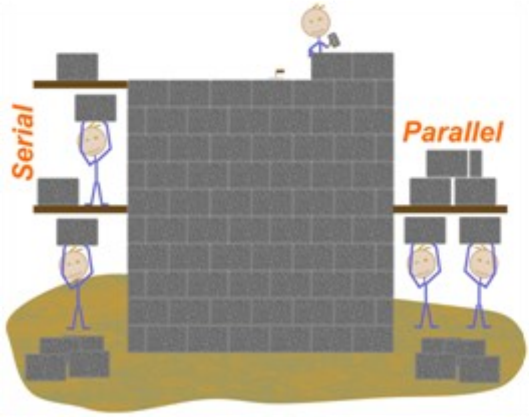
So what:

Analogies:

A building analogy -
The diagram shows builders lifting bricks for the top of a building.

The two builders on the left are doing it 'in series'. They achieve a greater height for the bricks but do not raise as many as the two on the right, who are working 'in parallel'.



Electrical analogy -
Batteries connected in series generate a higher combined voltage.
Batteries connected in parallel are capable of delivering a greater current.
The photograph shows how lithium batteries are connected some in series and some in parallel to generate high voltage and current needed by an electric (EV) car.

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Student Handout

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Worksheet 1 - Viscosity matters

Use the following formula to calculate the coefficient of dynamic viscosity η from your results:

$$\eta = \frac{2(\rho_s - \rho_g) \cdot g \cdot R^2}{9 \cdot V}$$

where ρ_s = density of the ball-bearing

ρ_g = density of glycerine = 1260 $kg.m^{-3}$

g = acceleration due to gravity = 9.81 $m.s^{-2}$

R = **radius** of the ball-bearing

V = terminal speed of the falling ball-bearing = **D** / **t**

Distance, **D**, from start line to bottom of tank = ... m

1. 2mm steel ball-bearing:

Sample number	**Time to fall distance D in s**
1	
2	
3	

Average time of flight **t** = ... s

Average speed of ball-bearings **V** = ... $m.s^{-1}$

Density of steel = 7900 $kg.m^{-3}$

Measured dynamic viscosity η = ... Pa.s

2. 3mm steel ball-bearing:

Sample number	**Time to fall distance D in s**
1	
2	
3	

Average time of flight **t** = ... s

Average speed of ball-bearings **V** = ... $m.s^{-1}$

Density of steel = 7900 $kg.m^{-3}$

Measured dynamic viscosity η = ... Pa.s

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Worksheet 1 - Viscosity matters .....

3. 4mm steel ball-bearing:

Sample number	**Time to fall distance D in s**
1	
2	
3	

Average time of flight **t** = ... s

Average speed of ball-bearings **V** = ... $m.s^{-1}$

Density of steel = 7900 $kg.m^{-3}$

Measured dynamic viscosity **η** = ... Pa.s

4. 5mm Delrin ball-bearing:

Sample number	**Time to fall distance D in s**
1	
2	
3	

Average time of flight **t** = ... s

Average speed of ball-bearings **V** = ... $m.s^{-1}$

Density of Delrin = 1420 $kg.m^{-3}$

Measured dynamic viscosity **η** = ... Pa.s

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Worksheet 1 - Viscosity matters .....

5. 6mm Delrin ball-bearing:

Sample number	**Time to fall distance D in s**
1	
2	
3	

Average time of flight **t** = ... s

Average speed of ball-bearings **V** = ... $m.s^{-1}$

Density of Delrin = 1420 $kg.m^{-3}$

Measured dynamic viscosity η = ... Pa.s

Official dynamic viscosity of glycerine = 1.5 Pa.s at 20^0C (depending on water content).

Comment on your results, highlighting possible major sources of error:

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Worksheet 2 - Calibrating the pressure gauge

Some formulae:

Theoretical value of pressure, **P**, exerted by the weights, is given by:

$$P = \frac{F}{A} = \frac{m \cdot g}{\pi \cdot R^2}$$

where **F** = force exerted by the weights;
m = mass added in kg;
g = gravitational field strength = 9.81 $N.kg^{-1}$;
A = area of piston = π x r^2;
r = radius of piston = 6mm = 6 x 10^{-3}m.

P will be in pascals (Pa) when **F** is in newtons (N) and **A** is in metres^2 (m^2).

$$Percentage\ error = \frac{gauge\ reading - theoretical\ pressure}{theoretical\ pressure} \cdot 100\%$$

Mass added in kg	Force applied in N	Theoretical pressure in kPa	Gauge Reading in kPa		Percentage error (%)	
			Loading	Unloading	Loading	Unloading
0.0	0.00	0.00				
0.1						
0.2						
0.3						
0.4						
0.5						
0.6						
0.7						
0.8						
0.9						
1.0						
1.1						
1.2						
1.3						
1.4						
1.5						

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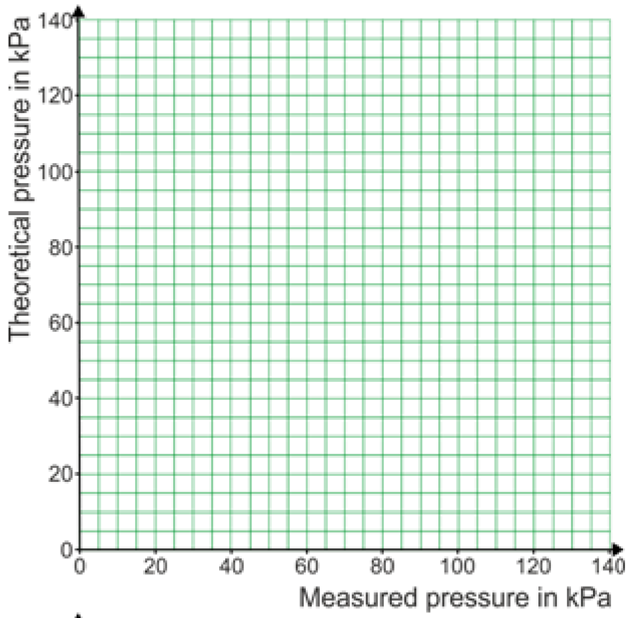
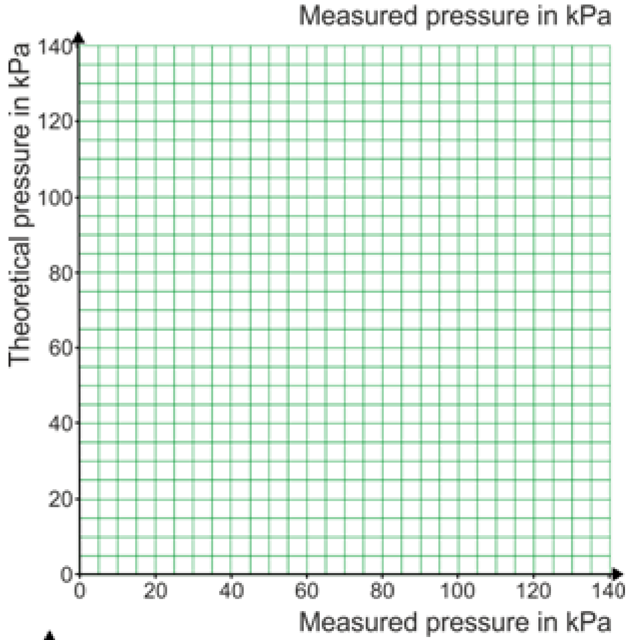
Worksheet 2 - Calibrating the pressure gauge .....

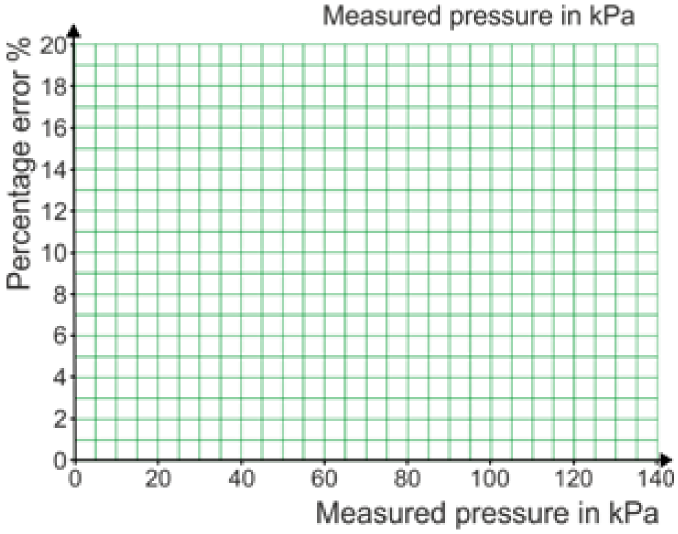
Increasing loads



Decreasing loads



Reading error



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Worksheet 3 - Using liquid-filled manometers

Some formulae:

The pressure, **P**, at the base of the water column in the single-limb manometer is given by:

$$P = \rho \cdot g \cdot h$$

where ρ = density of water = 1000kg.m^{-3}
g = gravitational field strength = 9.81N.kg^{-1}
h = height of water column in m.

$$Percentage\ error = \frac{Sensor\ reading - theoretical\ pressure}{theoretical +\ pressure} \cdot 100\%$$

Single-limb manometer:

Water column height in mm	Calculated pressure P in Pa	Diff. pressure sensor reading in Pa	Percentage error in diff. pressure sensor
0	0		
10			
20			
30			
40			
50			
60			
70			
80			
90			
100			

What do these results show about the performance of the differential pressure sensor compared to that of the single-limb manometer?

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Worksheet 3 - Using liquid-filled manometers

Some formulae:

The applied pressure, **P** is given by:

$$P = \rho \cdot g \cdot h$$

where ρ = density of water = 1000kg.m^{-3}
g = gravitational field strength = 9.81N.kg^{-1}
h = height difference in m between the left-hand and right-hand water columns .

$$Percentage\ error = \frac{Sensor\ reading - theoretical\ pressure}{theoretical + \ pressure} \cdot 100\%$$

U-tube manometer:

LHS column height in mm	RHS column height in mm	Height difference in mm	Calculated pressure P in Pa	Diff. pressure sensor reading in Pa	Percentage error in diff. pressure sensor

What do these results show about the performance of the differential pressure sensor compared to that of the U-tube manometer?

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Worksheet 4 - Inclined manometers

Water column height in mm	**Differential pressure sensor reading in Pa**		
	Angle of inclination = 90^0	Angle of inclination = 60^0	Angle of inclination = 30^0
0	0		
10			
20			
30			
40			
50			
60			
70			
80			
90			
100			

What do these results show about the performance of the inclined manometer compared to the other manometers?

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Worksheet 5 - Centre of pressure

Apparatus dimensions:

Distance **Z** from pivot to bottom of tank = ... mm = ... m
Length **L** of lever arm = ... mm = ... m
Width **B** of end plate = ... mm = ... m
Height **H** of end plate = ... mm = ... m

Total mass of mass hanger in g	Weight W of mass hanger in N	Depth of water D in mm	End plate submerged? (P or F)

To obtain the weight of the mass hanger, use the formula:

$$W = \frac{total\ mass\ in\ grams\ \cdot 9.81}{1000}$$

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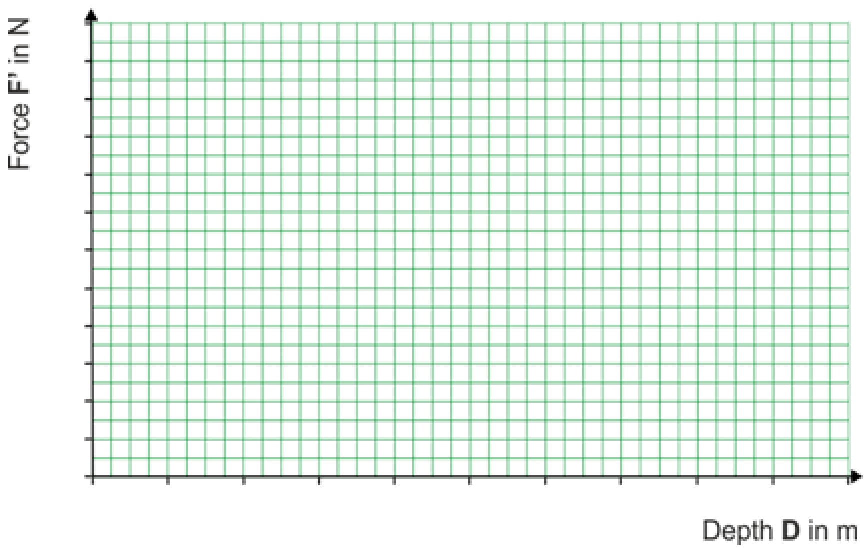
Worksheet 5 - Centre of pressure .....

Comparing experimental and theoretical results:

Depth of water D in m	Experimental value of Y in m	Theoretical value of Y in m

Results expressed as graphs:

1. **F' vs D:**



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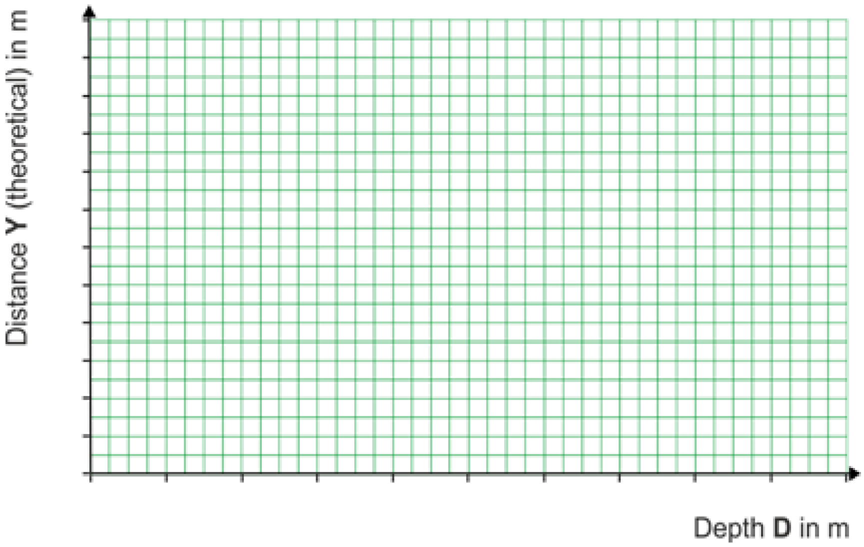
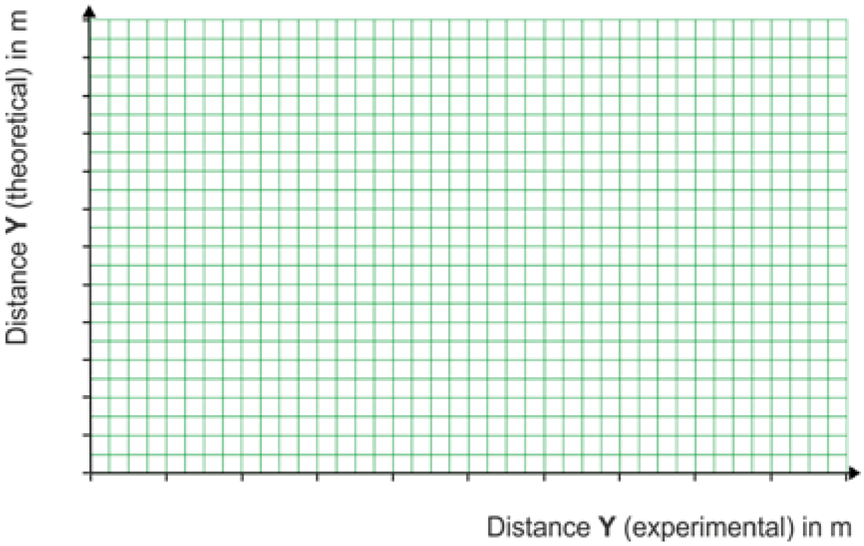
Worksheet 5 - Centre of pressure .....

2. Y vs D:



3. Y (theoretical) vs Y (experimental)



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Worksheet 5 - Centre of pressure

Comment on the shape of the first two graphs and what happens when the end plate becomes fully submerged:

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Comment on discrepancies between the experimental and theoretical values for the location of the centre of pressure:

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Worksheet 6 - Bernoulli's principle

1. Using the multitube manometer:

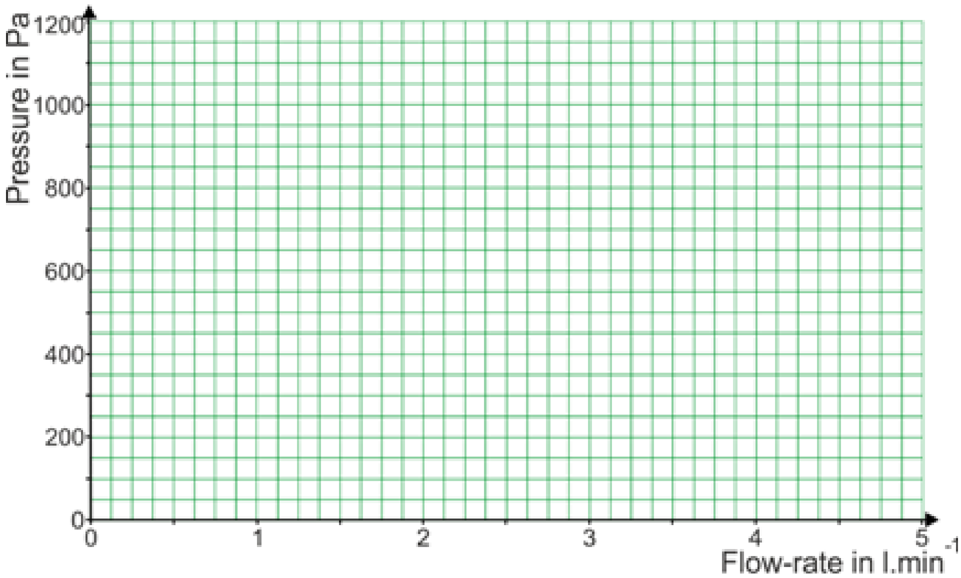
To calculate pressure difference Δp from column height difference (**h_2 - h_1**) **in metres** use:

$$\Delta P = (h_2 - h_1) \cdot \rho \cdot g$$

where ρ = density of water = 1000 kg.m^{-3} and g = gravitational field strength = 9.81 N.kg^{-1}

Pump voltage	Flow-rate in l.min^{-1}	Manometer height difference in m	Calculated pressure in Pa
18			
17			
16			
15			
14			
13			
12			
11			
10			
9			
8			
7			
6			

Graph obtained from these results:



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Worksheet 6 - Bernoulli's principle .....

Challenge 1:

When port 3 is connected to the manometer, what do you notice about the column heights upstream of the venturi compared to downstream? Suggest an explanation

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So what:

Having added the graph showing theoretical pressure plotted against flow-rate to that showing measured pressure against flow-rate, comment on the comparison:

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Challenge 2:

How did you proceed in trying to find the most appropriate value of $\mathbf{C_d}$ to model the behaviour of the apparatus and what was the result?.

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Worksheet 7 - Minor losses in bends

Pump voltage	Mitre bend		Tight bend		Gradual bend	
	Flow-rate in $l.min^{-1}$	Manometer height diff. h_{loss} in m	Flow-rate in $l.min^{-1}$	Manometer height diff. h_{loss} in m	Flow-rate in $l.min^{-1}$	Manometer height diff. h_{loss} in m
18V						
14V						
10V						
6V						

Use the formula to $K_{loss} = \frac{H_{loss} \cdot 2 \cdot g}{v^2}$ calculate a value for **K_{loss}** for each row:

Pump voltage	Mitre bend		Loss coefficient K_{loss}
	Flow-speed v in $m.s^{-1}$	Manometer height difference h_{loss} in m	
18V			
14V			
10V			
6V			

Pump voltage	Tight bend		Loss coefficient K_{loss}
	Flow-speed v in $m.s^{-1}$	Manometer height difference h_{loss} in m	
18V			
14V			
10V			
6V			

Pump voltage	Gradual bend		Loss coefficient K_{loss}
	Flow-speed v in $m.s^{-1}$	Manometer height difference h_{loss} in m	
18V			
14V			
10V			
6V			

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Worksheet 8 - Centrifugal pump

Comment on any deductions you draw from the sequence of graphs of flow-rate vs pressure.

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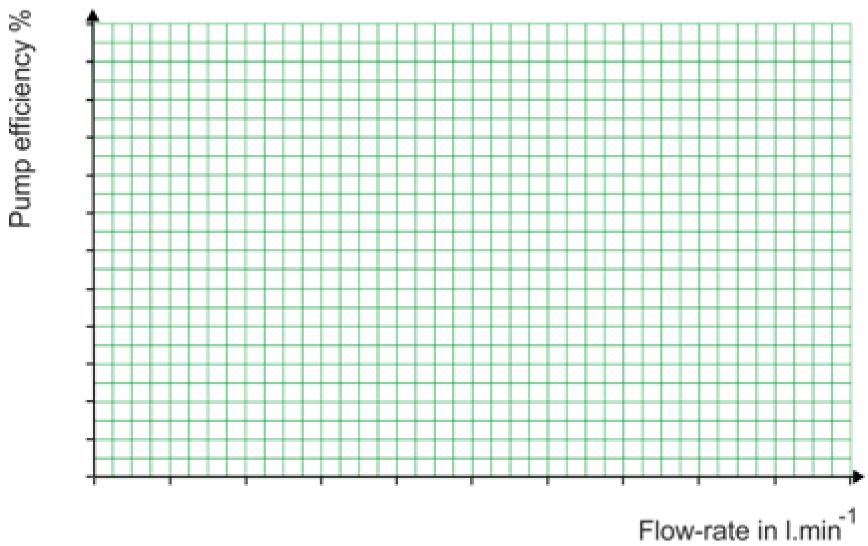
Challenge:

$$Pump\ efficiency = \frac{Water\ power\ delivered\ by\ the\ pump}{Electrical\ power\ supplied\ to\ the\ pump} \times 100\%$$

$$Water\ power\ delivered\ by\ the\ pump = Pump\ Pressure\ \times Volume\ flow\ rate$$

$$Electrical\ power\ supplied = Pump\ voltage\ \times Pump\ current$$

The variation of pump efficiency with flow-rate for a pump voltage of 24V.



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Worksheet 9 - Pumps in series and in parallel:

Pumps in series:

Comment on any deductions you draw from the sequence of graphs of flow-rate vs pressure.

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Pumps in parallel:

Comment on any deductions you draw from the sequence of graphs of flow-rate vs pressure.

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Notes for the Instructor

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Notes for the instructor

About this course

Aims and introduction

The ‘Fluid Mechanics’ module aims to introduce students to concepts involved in understanding and controlling the flow of liquids.

The course is based on a series of practical investigations using kit which can be used with minimum supervision that illustrate topics relating to fluid mechanics in BTEC National and Higher National courses.

Prior Knowledge

It is expected that students have followed an introductory science course, enabling them to take, record and analyse scientific observations. Some mathematical capability is required - ability to take readings from an analogue scale, ability to understand the transposition of formulae, ability to use a calculator to perform calculations and ability to plot a graph.

Using this course:

It is expected that the Worksheets and Student Handout are printed / photocopied, preferably in colour, for the students’ use.

The worksheets have:

- an introduction to the topic under investigation;
- step-by-step instructions for the investigation that follows
- a guide to analysing the results.

The Student Handout is a record of measurements taken in each worksheet and questions relating to them. Students do not need a permanent copy of the worksheets but do require their own copy of the Student Handout

This format encourages self-study, with students working at a rate that suits their ability. It is for the instructor to monitor that their understanding is keeping pace with progress through the worksheets. One way to do this is to ‘sign off’ each worksheet, as the student completes it, and in the process have a brief chat to assess the student’s grasp of the ideas involved in the exercises it contains.

We realise that you as a subject area practitioner are the lead in determining how and what students learn. The worksheets are not meant to supplant this or any other supporting underpinning knowledge you choose to deliver.

For subject experts, the ’Notes for the instructor’ are provided simply to reveal the thinking behind the approach taken. For staff whose core subject knowledge is not in the field covered by the course, these notes can both illuminate and offer guidance.

Time:

It is likely to take students between seven and ten hours to complete the worksheets.
A similar length of time will be needed to support the learning that takes place as a result.

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Notes for the instructor

Fundamental FLUIDS

Learning Objectives

On successful completion of this course, the student will be able to:

- explain the meaning of the term 'viscosity';
- describe under what conditions a falling object achieves its terminal speed;
- measure the terminal speed of a falling object;
- calculate the coefficient of viscosity using a given formula;
- state the limitations of applicability of that formula;
- describe how to calibrate a Bourdon pressure gauge;
- use the formula **P** = **F** / **A** to calculate the pressure exerted by a weight, **F**, on a surface of area **A**;
- calculate the percentage error in a gauge reading when comparing it to a calibrated reading;
- obtain and use a correction factor for a calibrated Bourdon gauge;
- describe how to use a U-tube manometer to measure fluid pressure;
- use the formula $\Delta p = (h_2 - h_1) \times \rho \times g$ to calculate the pressure difference between fluids in the limbs of a U-tube manometer;
- suggest a reason for a pressure head loss along a straight section of pipe;
- use a solid-state manometer and associated software to measure the pressure difference across a venturi nozzle and obtain a graph of pressure difference vs flow-rate;
- explain why the inclined manometer is more sensitive to changes in pressure;
- describe the effect of angle of inclination on sensitivity;
- describe one use for an inclined manometer;
- explain the meaning of the term 'centre of pressure';
- explain why the shape of the tank used simplifies the treatment of the processing of the results;
- use the principle of moments to obtain the force exerted on the end plate of the tank;
- explain why the treatment of the results depends on whether the end plate is totally submerged or not;

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Notes for the instructor

Learning Objectives .....

- use the conservation of mass formula, **q** = **v** x **A**, to link the flow-rate in a fluid to its speed;
- identify the three terms of the Bernoulli equation $\mathbf{p} + 1/2(\rho.\mathbf{v}^2) + \rho.\mathbf{g}.\mathbf{h}$ = constant;
- relate this Boolean equation to the conservation of energy theorem;
- use the conservation of mass equation and the Bernoulli equation to obtain an equation linking the flow-rate of a fluid to the pressure difference across a venturi nozzle;
- explain what is meant by the term ‘coefficient of discharge’ for a venturi nozzle;
- obtain an estimate of the coefficient of discharge for a venturi nozzle;
- describe three examples and three applications of the venturi effect in everyday life;
- give two examples of ‘minor losses’ occurring in fluid flow;
- explain, in terms of momentum, the pressure loss caused by a fluid flowing round a bend;
- compare the pressure losses caused when fluid flows around bends of different curvature;
- describe the significance of the ‘head loss coefficient’ for a bend;
- state the main advantage of the centrifugal pump over other designs;
- describe the relationship between flow-rate and fluid pressure;
- calculate the efficiency of a centrifugal pump;
- explain what is meant by the terms:
    - *pump curve*,
    - *system curve*,
    - *pump efficiency curve*
    - *duty point*;
- describe the relative performance of two identical pumps connected in series and two identical pumps connected in parallel;
- describe one analogy for the behaviour of pumps in series and in parallel.

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Notes for the instructor

Worksheet	Notes
Introduction Timing 20 - 30 mins	The introduction describes the contents of the kit and gives information about some of the modules it contains. Depending on their IT skills, the students may need help with the software application 'Fluids'. They need to know where to find it and how to access the results. For some investigations, they need permissions to take screen shots and store them where they can later be accessed. They may need help in understanding and setting up the 'Properties' used within the application. The instructor may regard the exercise in calibrating the flow-meter as a useful skill and require that students carry this out. If so, a pump voltage of 10V is suitable. Otherwise the task can be left to laboratory staff to check periodically. Students should be shown how to set up and prime the pump and pressure meters.
1 Viscosity matters Timing 40 - 60 mins	Concepts involved: viscosity terminal speed Stokes' law Reynold's number laminar flow sources of error The instructor could outline examples showing the importance of viscosity and some applications to engineering, such as lubrication. The formula used to calculate the viscosity is fairly involved and is repeated a number of times. It is probably best tackled using a spreadsheet, where students are confident about doing so. The final part of the investigation asks students to suggest likely sources of error that might account for discrepancies between their experimentally obtained viscosity coefficients and the official values, such as the true diameters of the ball-bearings compared with their nominal values.
2 Calibrating the pressure gauge Timing 30 - 40 mins	Concepts involved: fluid pressure Bourdon gauge percentage error reading an analogue scale The Bourdon gauge is a common form of pressure gauge found in industry. The instructor may wish to describe how it works or leave this as an exercise for the students to research for themselves. Regardless, students should be made aware that, like all measuring instruments, they are subject to systematic error. It is useful to discuss features of the percentage error graph in this regard.

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Notes for the instructor

Worksheet	Notes
3 Using liquid-filled manometers Timing 30 - 40 mins	Concepts involved: manometer differential pressure sensor The set-up procedure for both types of manometer is complicated and may need support from the instructor. If it is found that the pressure reading fluctuates, it may be necessary for the laboratory staff to adjust the 'LPF' (low-pass filter) setting in the 'Configurator' tool that is included in the software. Once again, it is useful to discuss percentage error for the two pressure sensors.
4 Inclined manometers Timing 30 - 40 mins	Concepts involved: sensitivity inclined manometer Once again it is important that the setting up process is carried out carefully. The investigation aims to demonstrate the significant increase in sensitivity obtained by inclining the manometer tube and the link between the angle of inclination and the sensitivity. The task can be streamlined by allocating different angles of inclination to different groups of students. Results can later be merged as part of a class discussion.
5 Centre of pressure Timing 40 - 60 mins	Concepts involved: centre of pressure moment of a force principle of moments The instructor may wish to outline significant features of the equipment, such as its shape. The method used to process the results is convoluted and may need further input from the instructor. Students could be asked to explain the relationship between centre of mass and centre of pressure. The formulae used to obtain the theoretical location of the centre of pressure are simply quoted in the investigation. Mathematically competent students may be tasked with researching them on the internet or even deriving these themselves.

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Notes for the instructor

Worksheet	Notes
3 Using liquid-filled manometers Timing 30 - 40 mins	Concepts involved: manometer differential pressure sensor The set-up procedure for both types of manometer is complicated and may need support from the instructor. If the pressure reading is found to fluctuate, it may be necessary to adjust the 'LPF' (low-pass filter) setting in the 'Configurator' tool included in the software. Once again, it is useful to discuss percentage error for the two pressure sensors.
4 Inclined manometers Timing 30 - 40 mins	Concepts involved: sensitivity inclined manometer The investigation aims to show that the inclined manometer is more sensitive to pressure changes and that sensitivity is linked to the angle of inclination of the tube The task can be streamlined by allocating different angles of inclination to different groups of students. Results can later be merged as part of a class discussion.
5 Centre of pressure Timing 40 - 60 mins	Concepts involved: centre of pressure moment of a force principle of moments Students could be asked to explain the relationship between centre of mass and centre of pressure. The instructor could outline the significance of the shape of the equipment and work through the convoluted method used to process the results. The formulae used to obtain the theoretical location of the centre of pressure are simply quoted in the investigation. Mathematically competent students may be tasked with researching them on the internet or even deriving these themselves.
6 Bernoulli's principle Timing 30 - 50 mins	Concepts involved: venturi Bernoulli's principle conservation of energy and mass coefficient of discharge Students could design presentations to identify the nature of the three terms in Bernoulli's principle and the links between them and the conservation of energy . By now, students should be familiar with the set-up and use of the manometer and pump. Explaining 'head loss' along the straight section of the tube could be another focus for a class discussion or presentation. The theory developed in the investigation is again tortuous and may need additional support from the instructor. The significance of coefficient of discharge and the results of the work done on it could form the basis for another class discussion / presentation / research.

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Worksheet	Notes
7 Minor losses in bends Timing 30 - 50 mins	Concepts involved: minor losses in flow loss coefficient An initial instructor-led discussion could focus on the meaning of 'major losses' and 'minor losses' in fluid flow, (as minor losses may not be minor!) Students should be familiar with setting up the equipment which must nevertheless be carried out carefully. The investigation compares the pressure loss resulting from three bends having different curvatures. Students could be asked to report their findings to the class.
8 Centrifugal Pump Timing 40 - 60 mins	Concepts involved: centrifugal pump pump efficiency The instructor may need to demonstrate how to take screen-shots, where to store them and how to print them out. This technique is used in both this worksheet and the next. The procedure used here may not be immediately apparent to some students. The pump voltage is set to 24V, its maximum, and so the resulting flow-rate is maximum for that setting of the flow-control valve. The app. steps the pump voltage down to 6V and monitors the effect on flow-rate as it does so. The process is then repeated for various settings of the flow-control valve. The diagram on page 36 could be used to introduce features involved in assessing pump performance, especially pump efficiency. The note about the units used for pressure and flow-rate should be stressed.
9 Pumps in series and in parallel Timing 30 - 50 mins	Concepts involved: series connection parallel connection Sometimes, an application requires more pressure or more flow-rate then a single pump can provide. Then a bank of several pumps must be used, connected in series or in parallel. It is important that students recognise these types of connections. The procedure is the same as that used in the last investigation. The pump voltage is set to its maximum then stepped down by the app. monitoring the flow-rate as it does so. The process is then repeated for various settings of the flow-control valve. Students then draw conclusions about and contrast the effects of these connections.

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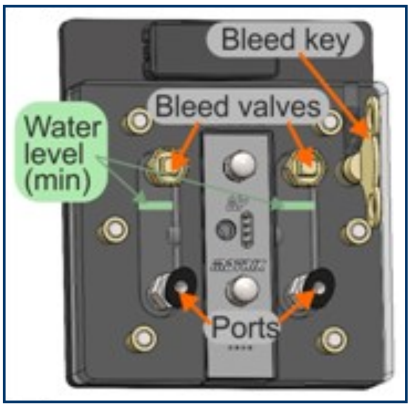
Differential pressure: sensor:

- The chambers are isolated from each other and must be adjusted separately.
- The level of water in each is regulated by using the 'bleed' key to open each bleed valve.
- In this way, fill the chambers to at least the level shown.



Recalibrating the differential pressure manometer:

The manometer arrives calibrated for use in the temperatures ranging from 15^{0}C to 20^{0}C. Outside this temperature range, it may need to be calibrated to achieve full accuracy. This requires the use of a simple U-tube water-filled manometer.

Method:

- Use the 'Configurator tool', supplied with the kit, to set the scale factor of the pressure sensor to 1.
- Connect one side of the U-tube manometer (provided one?) to the left-hand port of the pressure sensor module
- Leave the right-hand port and the other side of the U-tube manometer open to ambient air pressure.
- Ensure that the water in both sides of the U-tube is at the same level and click 'zero' on the software.
- Add positive pressure to the left-hand pressure port by raising the right-hand side of the manometer in small steps.
- After each increment, record the sensor reading shown on screen along with the height difference between left and right-hand sides of the U-tube manometer.
- Plot the results using the spreadsheet provided in the 'Fluids Control' application to determine the correct scaling factor
- Re-enter the scaling factor (use absolute if existing value =1, otherwise use relative).

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