ENME 314
Engineering Fluid Mechanics

LABORATORY MANUAL

1. Introduction. Lab Book Instructions and Assessment
2. Engineering Measurements in Fluids
3. Measurement Error and Data Analysis
4. Lab Instructions
5. Appendices

SAFETY AND BEHAVIOUR IN THE LAB

- Closed-toe shoes must be worn at all times in Mechanical Engineering Labs.
- Long hair and flowing clothes must be tied up.
- Identify potential hazards. Review the Fluid Mechanics Laboratories Hazards Assessment & Control Form.
- Safety instructions must be followed. Act responsibly. Follow the instructions given by the TA and lab manager.
- All equipment must be kept in good condition and in its place.
- Always bring a pen and straight edge for drawing, a calculator, your lab book and this lab manual to the labs.
- You must have a Teaching Assistant (TA) sign the work you did during the lab or it will not be graded.

INTRODUCTION TO ENME314 LABS

This LAB MANUAL contains all the information and instruction for the labs and lab assignments in ENME314. These laboratories will help reinforce key concepts from the course.

- **Lab A Part I: Pressure and Flow Measurement**
- **Lab A Part II: Aerodynamic Drag and Momentum**
- **Lab B: Dimensional Analysis and Boundary Layer**

Learning Objectives:

1. Practice a methodical approach to practical work and analysis
2. Learn to make accurate observations, measurements and error analysis;
3. Follow engineering standards for recording and reporting data and analysis;
4. Produce engineering test reports on the experimental work conducted.

You will need to read the material in this lab manual before attending each lab. There will be teaching assistants overseeing the lab, but you will need to work out how to complete the work, using the information in this manual. You will need a lab book to record your observations and raw data.

LAB SCHEDULES

You must attend your scheduled lab.

You MUST BRING A Lab Book and this LAB MANUAL to every lab. When you exit the lab, the TA will sign the data collection and observation sections in your lab book. You can add more to your report after you leave, like analysis, plots and discussion, but you cannot alter the data.

MY LAB **A** DAY ________________________ LAB **A** TIME ____________________________
MY LAB **B** DAY ________________________ LAB **B** TIME ____________________________
Lab Partners and Contact Details:

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ASSESSMENT

You are strongly encouraged to attend and pass all of the labs. There will effectively be three labs (Lab A Part I, Lab A Part II and Lab B). You will submit your Lab Book with the hand-written records of lab work and relevant graphs, calculations, analysis and discussion to be graded. The Lab BookS must be submitted <u>due two weeks after you have taken your lab</u>, by 5 pm on the same day of the week your lab day was. The drop box is on Level 2 of Mech Eng Lab Wing, on the mezzanine above the R.J. Scott Atrium.

LAB BOOK FORMAT AND ASSESSMENT CRITERIA

You will need to buy a personal Lab Book, which is an A4 notebook of at least 20 leaves marked with your name. By keeping a Lab Book you will learn about accurate documentation of engineering investigations and recording of data. In each laboratory class you will carry out a series of measurements. The Lab Book is an accurate and true recording of measurements and presentation of experiment conditions, observations and analysis. You can do calculations and paste plots from analysis of your data into your lab book after the investigations. You can also paste in pictures to back up your observations.

There is no "Lab Report" for Lab A. We will grade your Lab Book, including the observations, schematic diagrams, measurements, error analysis, and reflections on the things you learned and any post-lab analysis. This will be done on the basis of how complete and accurate the observations and data were recorded and how clearly that information is presented.

All Lab Book entries MUST have:

1) TITLE, NAME/S OF GROUP MEMBERS, LOCATION and DATE: Put your name and student number as a header on any loose printed pages.
2) PURPOSE: an aim.
3) SCHEMATIC DIAGRAM: Operation and points of measurements. This can be a photo of the set-up printed and can be added later.
4) BACKGROUND: This does not need to be a large excerpt of textbook information. Only a diagram of the system, assumptions, knowns, unknowns and the governing relations. (Hint; these can be found in each labs' instructions.)
5) EXPERIMENTAL PROCEDURE AND MEASUREMENT DEVICES: Any observations from the experiment and information about the device's accuracy. A brief outline of the experimental procedure would be a good idea but don't go through and repeat everything the instructions said.
6) DATA, ANALYSIS AND RESULTS: Raw data, plus interpreted data presented as tables, charts or figures.
7) DISCUSSION: Comments on test set-up and results. Comparison of experimental and theoretical values where applicable. Sources of inaccuracy and experimental error. Error propagation.
8) RECOMMENDATIONS/CONCLUSION: Any implications of the experiment. Think back to the aim.
9) References for any sources of information you have used.

Write simply and clearly. One idea per sentence.

For Lab B, you will submit a brief, formal report (details later in this manual).

Marking Schedule:

Completeness (the 8 things above)	scale of 1 to 5
Accuracy (including error analysis)	scale of 1 to 5
Clarity	scale of 1 to 5
Precision (no extra padding, easy to find information)	scale of 1 to 5
Results reporting	scale of 1 to 5
Analysis and Conclusions	scale of 1 to 5

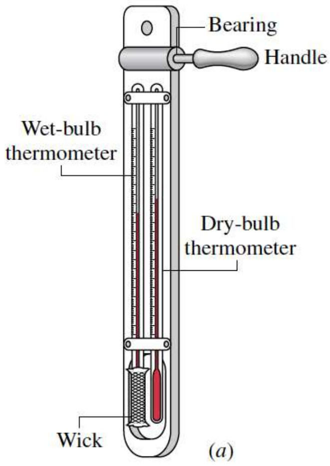
1. ENGINEERING MEASUREMENTS

Experimental investigations in fluid mechanics often involve measurements of temperature, pressure and flow rate. There are a number of measurement methods and it is important to choose a method appropriate to the expected range of parameter, the required accuracy, the response time and the conditions under which the measurement will be taken.

In this section, some of the measurement devices you will come across in this laboratory course are introduced, the way they work is explained, and some of their limitations and sources of error are discussed. For an interesting look at the possibilities for engineering measurements, visit www.omega.com.

Temperature

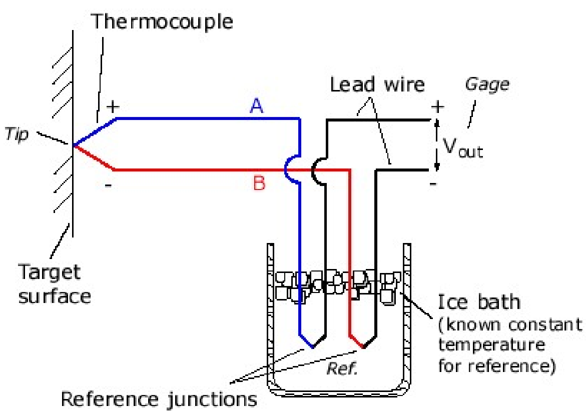
Bulb thermometer



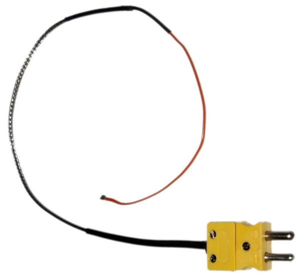
The bulb thermometer uses the thermal expansion of a fluid in a metered glass tube. It is important to have the bulb end of the thermometer completely contacting the substance or immersed in the fluid being measured. If measuring the temperature of air, there are two options. Dry bulb temperature is measured with the bulb exposed directly to the air. Wet-bulb temperature is measured by saturating a porous wick, placed around the bulb of the thermometer, with water. The thermometer is then rotated so that the wick reaches the lowest temperature possible by evaporation into the air. This wet bulb temperature is affected by evaporation, so is a function of the air temperature and the relative humidity. As humans sweat, wet bulb temperature relates to human comfort in the environment.

Thermocouple

The thermocouple is a junction of two dissimilar metals. A small voltage is produced along the wires which is a function of the temperature difference between the junction and the reference junction. By measuring this voltage, compared to a “cold junction” reference voltage, the temperature of the junction can be determined using calibration or a calibrated electronic gauge. Where the two wires touch, the thermocouple junction, must be placed within intimate physical contact with the object or substance, so that it is in thermal equilibrium with the substance to be measured. Thermocouples are calibrated against bulb thermometers or known physical states, like an ice/water bath or boiling water.



Type T: Cu &CuNi
-270°C to 400°C



Type K: Ni-Cr & Ni-Al
-270°C to 1372°C

Thermocouple principle and different types

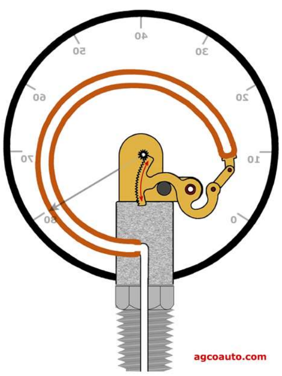
Thermocouples come in a variety of types (i.e. J, K, T, E etc.) depending on which two metals they are made from. The most common thermocouple you will encounter is the type K thermocouple. These are made from chrome and aluminium wire. The wires and junction must be electrically insulated.

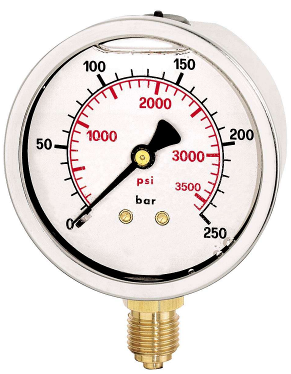
Thermocouples are a low cost and safe method of measuring temperature and have advantages over thermometers as they are more rugged, do not contain liquid mercury and provide an electrical output signal. The thermocouple junction temperature provides the measurement. However, the junction temperature is a *function* of the temperature of the gas or liquid or solid that is being measured. You must understand the processes of heat transfer in order to ensure that the thermocouple is close enough to thermal equilibrium with the substance being measured. Radiation to or from the surroundings, heat convection from the thermocouple and heat conduction along the thermocouple wires can cause the reading to be different from the actual state.

Pressure

Two common methods of measuring pressure include the Bourdon gauge and the manometer. Neither of these produce an electrical signal.

Bourdon Gauge
The Bourdon gauge was invented in France in 1849. It consists of a curved metal tube which is slightly flattened and attached via a threaded connector into the pipe or tank where pressure is to be measured. The tube is attached to a mechanism which turns a dial. As the pressure rises, the tube straightens slightly causing the dial to turn. You will notice that many of the gauges in the





Pressure Units

1 atm = 1.01325 bar
1 atm = 101.325 kPa

1 atm = 14.696 psi
1 atm = 760 mmHg
1 atm = 760 Torr

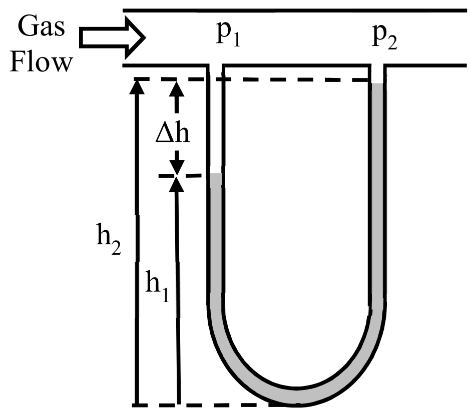
laboratories are filled with a fluid. This fluid is usually some kind of viscous oil or glycerine which damps the movement of the needle allowing for easier reading of the output, prevents moisture build up inside the gauge and protects the mechanism from vibration damage.

Manometers

A manometer is a device which measures a *differential* pressure, or the difference between two pressures. Manometers can be used to measure the difference between one pressure and a reference pressure, which may be a sealed vacuum chamber in the instrument, a different point in the system, or the atmosphere.

U-Tube Manometer

U-Tube Manometers consist of a glass or clear plastic tube partially filled with a liquid (usually water, and rarely, mercury). The pressure difference can be determined from the height of the liquid "columns" on either side of the U-tube through hydrostatics, as shown in the following example:



Gas flows in a pipe and because of friction with the pipe walls the pressure drops so that $p_1 > p_2$. Thus, p_1 exerts more force on the liquid in the manometer than p_2 causing a height difference in the two columns of liquid $h_1 < h_2$.

The height difference of the two columns of liquid $\Delta h = h_2 - h_1$ and from Newton's second law we know that:

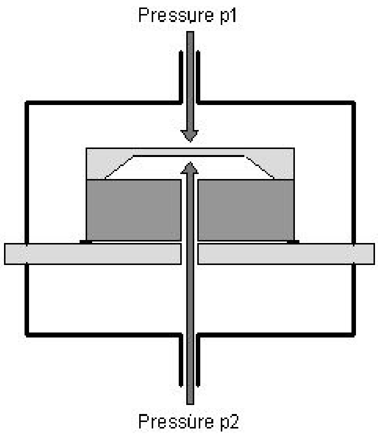
$$\Delta p = \frac{F}{A} = \frac{mg}{A} = \frac{\rho V g}{A} = \frac{\rho \Delta h A g}{A} = \rho g \Delta h$$

Where g is the acceleration due to gravity and ρ is the density of the liquid in the manometer.

Thus we can measure the pressure difference in the gas by measuring the height difference between the two columns of the manometer liquid. Note that we do not have to know the velocity or density of the gas in order to make this measurement.
The common use of water, and more rarely mercury, in manometers, and the measurement of a height as a proxy for pressure, gave rise to the common use of the units millimetres of water (mmH_2O) and millimetres of mercury (mmHg), equal to the height h. Note these are not SI units and if you take a reading in them, you should convert to Pascals.

Mercury barometer

The mercury barometer has a closed end attached to a chamber under vacuum. If $p_1 = 0$ then the height of the column of liquid gives a direct measurement of the absolute atmospheric pressure. Mercury is chosen because of its high density which means that the barometer can be relatively small in size.



Strain gauge pressure sensor
A common electronic pressure transducer uses a wafer which separates a reference pressure (often atmospheric pressure) from the pressure to be measured. The wafer flexes as pressure changes, and strain gauges measure how much it moves. The strain gauge signal is converted into a pressure by onboard electronics.

Gauge and absolute pressure

Always pay attention to whether your instrument reads *gauge pressure*, p_g, or absolute pressure p. The absolute pressure is the gage pressure plus the reference pressure p_a.

$$p = p_g + p_a$$

If your pressure sensor reads 0 when exposed to atmosphere. Clearly, the pressure in the room is not zero, it is atmospheric pressure.

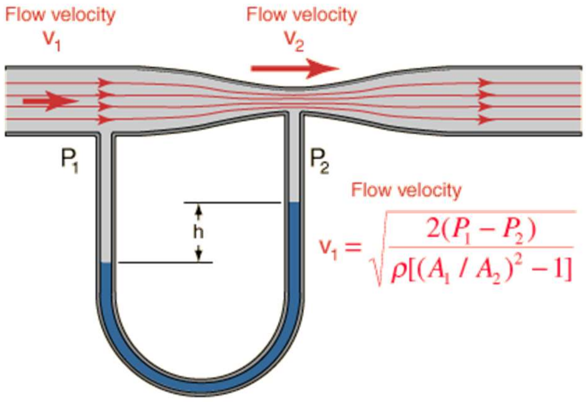
Differential sensors
If your pressure sensor has two fluid connections, it reads the difference in pressure between these (differential pressure). The second fluid connection might be just a tiny vent to expose the instrument to atmospheric pressure. If the sensor truly has only one fluid connection, it reads the difference in pressure between that connection and a reference pressure, which may be absolute vacuum, or some other pressure. Check the label or data sheet for your sensor to be sure.

Fluid Flow Rate

There are many methods for measuring fluid flow by volume [m^3/s] or by mass [kg/s]. Physical measurement of phenomena caused by the flow are used for calibration, precise measurement, or just for a visual check that the fluid is flowing. Electronic transducers are used to generate a signal for monitoring and control of processes.

Bucket and Stopwatch

This is a simple method for liquids. You collect flow from a process in a vessel over a certain amount of time, measure the volume (or mass) collected, divide the volume by the time, using the density of the fluid at the flow temperature to improve accuracy.



Venturi Flowmeter

The Bernoulli principle can be used to measure flow rate. The Venturi meter has to be built into the process and have known cross sections A_1 and A_2.

Orifice Plate

The orifice plate is a low cost flow meter. The orifice plate, like the Venturi tube requires a straight section up-stream and downstream of the measurement to produce fully developed flow. It also uses the Bernoulli principle.

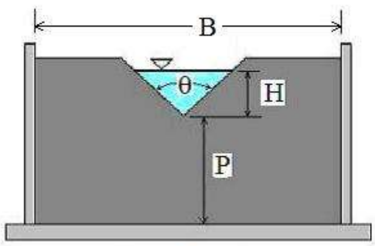
For both venturi and orifice plate, a calibration factors called the discharge coefficient, C_D, is used to obtain a measurement of flow from the pressure difference, the orifice (or throat) size and pipe size. The exact value of C_D depends on the shape of the orifice, the placement of the pressure taps and the fluid properties. The discharge coefficient, C_D, for a venturi or an orifice is determined experimentally by the manufacturer. The volume flow rate is derived from the Bernoulli equation:

$$Q = C_D A_2 \sqrt{\frac{2(p_1 - p_2)}{\rho\left(1 - {A_2^2}/{A_1^2}\right)}}$$

The orifice plate has a large pressure loss compared to the venturi.

V-Notch Weir

The V-Notch is used to measure flow in an open channel. A float or other device can be used to measure the height of water in a stilling pond behind a calibrated notch. The main factor in the calibration is the angle of the notch, θ, and the discharge coefficient, C_d. In cubic feet per second:



V Notch Weir

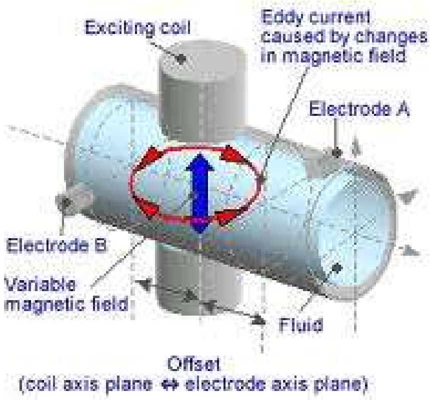
$$Q_{fluid} = C_d 4.28(H)^{5/2} \qquad \text{for a } \theta = 90^\circ \text{ notch } C_d = 0.58$$

Weirs with different shape notches are also used, and have different sensitivities.

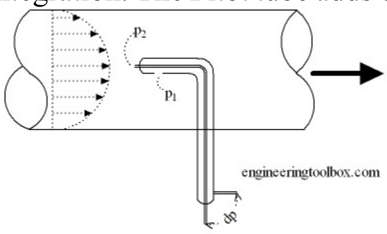
Electromagnetic Flow Meter

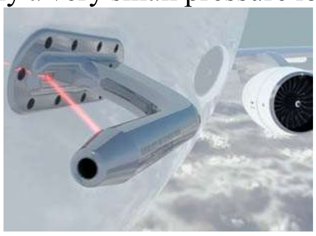
This type of flow meter has high precision and a direct electrical readout, which can be easily interfaced to a computer for data logging and use in automatic control. An electromagnet applies a magnetic field across a pipe section. The fluid flowing through it must be conductive. Tap water is sufficiently conductive to give a good signal. The meter does not need to be re-calibrated for different fluids. By Lenz' law an electrical potential must be set up at right angles to the fluid motion and to the magnetic field. A set of electrodes detects this electrical potential, the strength of which is proportional to the average fluid velocity and hence the flow rate. This meter does not impose a noticeable pressure drop on the flow.

The electromagnetic flow meter usually reads out in units of percentage of the maximum flow rate it can register. This maximum flow rate is stamped on a plate on the meter body. Convert the percentage to a fraction, and multiply it by the maximum to find the actual flow rate.



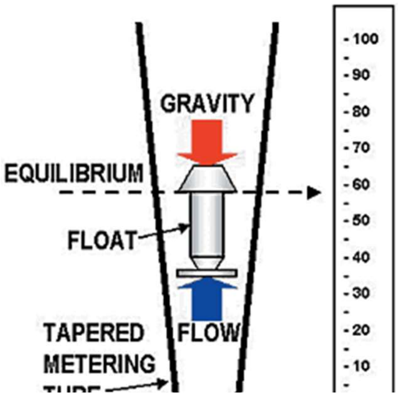
<u>Pitot Tube</u>
Commonly used in aerospace, this device requires a pressure sensor to determine the flow velocity. The tube is inserted into the flow to be measured. It has to be placed precisely in the centre, and the velocity gradients known, or it has to be traversed across the duct to make measurements in several places for integration. The Pitot tube adds only a very small pressure loss when measuring flow rate.





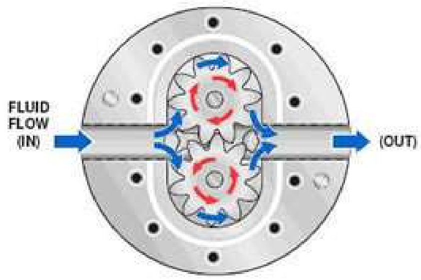
Rotameter

The variable area flow meter, or rotameter, uses drag force on a float to indicate the flow rate. Due to drag, the float rises against its weight proportionally to the flow rate. Rotameters can be used for liquids or gas, but the float and pipe size and material must be specifically sized and calibrated for the fluid and the fluid flow range and corrected for the fluid density at the measurement pressure. Each float is calibrated for the flow reading to be referenced to a certain part of the float, some use the top, spherical floats usually use the centreline, and some use the bottom. The measurement has very low pressure drop.



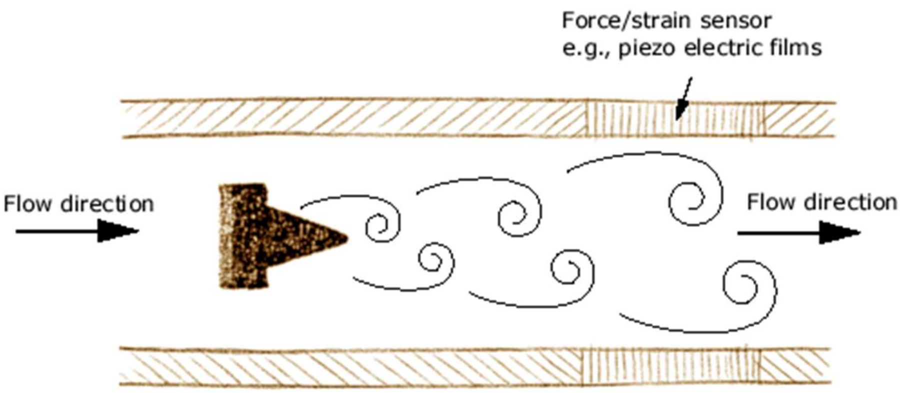
Positive Displacement Flow Meter

This device uses the fluid to turn a rotor system which seals off packets of flow as it turns (e.g. the fluid in the spaces between the gears in the diagram). The rate of rotation is a function of flow rate. There are several designs with different rotor systems.



Vortex Shedding Flow Meter

A vortex shedding flow meter has an object in the flow of the fluid that generates vortices behind the object. The rate at which vortices are generated is related to the velocity of the fluid. The frequency at which vortices pass is sensed by strain gauges on the tube wall downstream, or a pressure sensor, or by the cooling of a heated element. Vortex shedding meters have a direct electrical output and a low overall pressure drop.



2. MEASUREMENT ERROR AND UNCERTAINTY

There are always errors in engineering measurements. This does not necessarily mean a mistake has been made. It is not acceptable to make a mistake and then report the result! You would re-do the measurement until you got it right. However all engineers know that no measurement is perfect. You measure a value for example the temperature of a metal casing. Your instrument reads the “measured value”. Imperfections in your thermometer, or the way it can be read, mean this measured value differs from the true temperature (“true value”). The “error” is the difference between the measured value and the true value. If you know exactly what this error is (say, you know your thermometer always reads 1 ^{o}C higher than the true temperature), you subtract it from the measured value to get something closer to the true value (this is called correction). However, even if you do this carefully, there will always be some error that you can’t know exactly. Therefore, you define an uncertainty, which is a range either side of the measured value in which you are reasonably confident that the true value lies. This range is called the uncertainty:

Reported Value = Measurement Value +/- Uncertainty [units]

Meaning the true value is expected to be greater than Measurement Value-Uncertainty but less than Measurement Value-Uncertainty.

For example $T = 215 \pm 5$ ^{o}C means you think the true value lies between 210 and 220 ^{o}C.

You should not state a measured value to more significant figures than the uncertainty permits.
For example if you write a measurement as 215.638 +/- 5 ^{o}C, the .638 means nothing. Write this as 215 $\pm$ 5 ^{o}C.
If you measure 1325 mm to an uncertainty of +/- 10 mm, write 1330 +/- 10 mm.

A measurement which has a known uncertainty is much more valuable than one without. If you know a machine has a mass of 980 kg and you have a crane with a safe working load of 1000 kg, it might be safe to lift the machine, or it might be too heavy for the crane. If you know the mass of the machine is 980 +/- 10 kg, it can’t be heavier than 990 kg, and you know it’s safe.

Uncertainty in a measurement has two components:

Accuracy
Accuracy means how close your measurement is to the truth. We work on improving our measurement methods to get more accuracy. Accuracy can be poor because an instrument always measures too high or too low in a repeatable way. Calibrating our instruments makes them more accurate, e.g. checking our thermometer against an ice/water mixture to know that it always reads 1 ^{o}C too high, and correcting the measured value.

Precision
Precision is about how repeatable the measurement is. It is reflected in the number of significant figures in your measurement. Let’s say your thermometer measures 1.0 ^{o}C too high every time you make a measurement. Your thermometer is not accurate (it reads the wrong value) but it is precise. You know if you subtract 1.0 ^{o}C from the measurement it will be much closer to the true value.

However if you make four measurements of a temperature that you know to be constant, and you get measurements of 215.5, 215.6, 214.5 and 214.9 °C, you know you have a variable error. This might be a problem with your method (e.g. you can't put the temperature probe in exactly the same place every time) or a problem with your instrument (e.g. noise in the electronics). The severity of this variable error sets the *precision* of the instrument. In this case, over four measurements you get a precision of 1.0 °C (the biggest difference between any two results). (In practice you'd make a minimum of three measurements, and if you have time, ten or more, to see what the worst case was).

An instrument with good precision (small variability) but poor accuracy can be made better by calibration. An instrument with poor precision can't be made better, but taking many measurements and averaging will get you closer to the true value, if the variation in the measurement is random.

For instruments with a scale that's read by eye (like a ruler), one way to estimate the precision is half of the smallest increment on the scale, or greater. So for a ruler with 1 mm markings, the precision is 0.5 mm. The human eye can't read that scale to any better than 0.5 mm precision.

Good instrument makers provide estimates of the uncertainty. Look for this in the manual, datasheet or sometimes marked on the device.

Systematic errors

Systematic errors are constant, or depend on the measured value: e.g. reading 1°C too high, or always reading 10% too high. These affect accuracy, and can be corrected by calculation (if the physical reasons for the error are known) or calibration.

Random errors

There can be random errors in measurements that will even out if you take several measurements and average them. Think about trying to read a weighing scale during an earthquake. Half the time the reading would be too high as the ground accelerates up, and half the time it will be too low as the ground accelerates down. Random errors affect precision. However if you took 10 measurements during a quake, and averaged the vales, that would be closer to the real measurement than just one measurement (do not try this at home, there are more important things to do during earthquakes). To arrive at the *best* value, take the average value of *at least 3* measurements. Take more if the measurements are not close together (e.g. within 10%).

$T_{best} = average$ (of repeated measurements)

Then you can define the Variability = $\pm\ T_{max} - T_{avg}$

Experimental Error

Placing the measurement device into the system to measure a property will change the system. Good experimental design and methods can reduce the experimental error. A thermocouple provides a pathway for heat to be conducted away from the materials being measured, making them cooler than they are when the thermocouple isn't there. Also, the heat transfer to or from the thermocouple can cause it to be a different temperature than the substance to be measured. This is called *thermal shunting* and can be minimised by using smaller diameter thermocouple wires.

Example 1:

Look at the thermocouple reader in the picture to the left. The display is rounded to the nearest tenth of a degree, so we can be pretty sure that the temperature is no more than 52.05 ^{o}C and is at least 51.06 ^{o}C. Our measurement does not have 4 significant figures, however, because the measurement is only precise to 3 figures. Thus, we would report the measurement as T = 52.0 ± 0.05^{o}C. You take three measurements with this meter and average them and your calculator says:

52.0 52.1 52.1 *average* = 52.0666667

To report this measurement, you write:

T = 52.1 ± 0.05 ^{o}C

Example 2:

The thermometer to the right has labelled increments of 1 degree, with ten divisions. We can distinguish between 36 ^{o}C and 38 ^{o}C with high certainty – the temperature is definitely 38 and not 36. We can make a good estimation of whether the liquid inside is closer to 37.8 or 37.9 ^{o}C because we will go with the lower value if the liquid is less than halfway between, and the higher reading if it is more than half way between (i.e. use rounding). However, we cannot accurately say if the temperature is 37.85 or 37.86 ^{o}F. We would report the temperature reading accuracy as:

T = 38.8 ± .05 ^{o}C

We have three significant figures, and we are estimating the tenth of a degree within the half-way point between marks.

Percent or Relative Uncertainty

The error can also be reported as a percentage of the measurement.

The percent error is easy to calculate just divide the error by the measurement value.

% = 100x$\Delta T/T$

Example 2 above has an uncertainty of 0.13%

Reporting the Measurement Uncertainty:

A lot of instruments will use % error in their product specifications. The thermocouple reader pictured on the previous page has specifications listed as:

- Temperature range: -250°C (-418°F) ~ 1767°C (3212°F)
- Accuracy: ±(0.05% + 0.3°C) not including thermocouple error (±1-5 ^{o}C depending on grade of wire)

Just from looking at the display we estimated accuracy of 0.05^{o}C, but the manufacturer's accuracy at that temperature would be 52x0.05/100+0.3=±0.33 ^{o}C. Which one should we use?

In your lab book, you would write a section to record the uncertainty for each measurement:

Example: Temperature

Resolution: Thermocouple reader meter display resolution = 0.1 ^{o}C

Accuracy: Fluke 52 manufacturer data $\Delta T \pm 0.05\% + 0.3^{o}C = \pm 0.35\ ^{o}C$
Transducer Error: Manufacturer data Type K thermocouple ± 3 ^{o}C
Experimental Error: Radiation + conduction cooling of the junction to surroundings
Variability: Over 3 min, $T_{min} = 50.5$ $T_{max} = 53.4\ ^{o}C$

When you write the measured value subsequently, state only the largest of the uncertainties. In this example, the biggest uncertainty comes from the thermocouple, so if you measure 45.9 ^{o}C you write: 50 ± 3 ^{o}C

In any report, always state the units, every time you write a value. State the uncertainty at least once when you first write the measured value, and again in any conclusion, and as often as you think sensible in between.

Uncertainty Propagation

You have made all your measurements, recorded the average values, and have your uncertainty for the measurement (use the largest one). Now you want to calculate some value Q from your measurement. You might use two parameters, x and y, each of which has an uncertainty which can affect the final calculated value. What is the uncertainty in that calculated value? There are rules for *propagating* the uncertainty to get an estimate of the uncertainty $\pm\Delta Q$ in a calculated quantity, Q. There are two ways of propagating errors, quadrature addition and direct addition.

Use **quadrature addition** if you think the errors have a random element to them. They will often cancel each other out e.g. a positive error in x is partly balanced by a negative error in y. This is the case for most errors.

Addition or Subtraction: $Q = x + y$ or $Q = x - y$

Then: $$\Delta Q = \sqrt{(\Delta x)^2 + (\Delta y)^2}$$

Multiplication or Division: $Q = xy$ or $Q = x/y$ etc.

Then: $$\Delta Q = |Q|\sqrt{\left(\frac{\Delta x}{x}\right)^2 + \left(\frac{\Delta y}{y}\right)^2}$$

Multiplying or diving by a known constant with no uncertainty (e.g. pi)

$$Q = \mathrm{A}x$$

$$\Delta Q = |\mathrm{A}|\Delta x$$

Other functions (powers etc.): $Q=f(x)$ Then: $\Delta Q = \left|\frac{dQ}{dx}\right|\Delta x$

$Q=f(x,y)$ Then: $$\Delta Q = |Q|\sqrt{\left(\left|\frac{\partial Q}{\partial x}\right|\Delta x\right)^2 + \left(\left|\frac{\partial Q}{\partial y}\right|\Delta y\right)^2}$$

Quadrature addition gives a lower uncertainty than direct addition.

If you think the errors might not be random (i.e. they are systematic), then use **direct addition** to get a 'worst case' if the error in x and y reinforce each other:

Addition or Subtraction: $Q = x + y$ or $Q = x - y$ and $Q = \mathrm{A}x$

Then: $\Delta Q = |\Delta x| + |\Delta y|$

Multiplication or Division: $Q = xy$ or $Q = x / y$ etc.

Then: $\Delta Q = |Q| \left(\left| \frac{\Delta x}{x} \right| + \left| \frac{\Delta y}{y} \right| \right)$

Multiplying or diving by a known constant with no uncertainty (e.g. π)

$Q = \mathrm{A}x$

$\Delta Q = |\mathrm{A}|\Delta x$

(i.e. same as in quadrature addition)

Other functions (powers etc.): $Q=f(x)$ Then: $\Delta Q = \left| \frac{dQ}{dx} \right| \Delta x$

(same as in quadrature addition)

$Q=f(x,y)$ Then: $\Delta Q = |Q| \left| \frac{\partial Q}{\partial x} \right| |\Delta x| + \left| \frac{\partial Q}{\partial y} \right| |\Delta y|$

Other points about recording and presenting data

When you make a series of measurements, you are recording your observation of the reading of an instrument that is only *related* to the actual phenomena you want to know about. It is not the actual phenomenon, it is filtered and distorted by inaccuracy and imprecision. You then interpret the accuracy of that observation by recording the accuracy and the error and the conditions that might have affected that reading. You need to record the data in a way that preserves all of this information. After you collect the data, you will present it, usually in tables, charts and graphs. When you make a graph or chart, you actually start interpreting the information, which can be good in that it enhances the understanding of the actual phenomena, or it can be misleading. Below are some basic concepts and rules of presentation to be aware of.

Raw Data

The original, real time observation of the instrument reading is call *raw data.*

First: think about the data you will be taking and make a table in your lab book. Label the rows and columns. Each column label should include the unit. If the data has a functional relationship, Q = f(x) where you control x directly, then x is the independent variable and should be in the first column with Q in the second column.

Remember that you will be taking at least 3 readings of each measurement, so structure your table accordingly (you might have three columns for Q).

The standard format of a table in scientific and engineering communication is shown below.

- Have heavy lines at the top, bottom and below headings. You can have other grid lines if you want, but you might not need them all.
- Name of table above the table

- Units given in headings
- Headings bold
- Use justified text

Table 1. Data from heat transfer experiment to measure boiling rate

Time [s]	**Liquid Temperature [^oC]**	**Mass of Liquid [g]**	**Pressure [kPa]**
0	92	480	189
260	98	400	230
480	102	398	268

Physical Properties (e.g. density, viscosity)

An error of ±2 ^oC in temperature measurement leads to error in the fluid property values you look up. Most tables of properties are arranged so that linear interpolation between data points is accurate.

Analysis

Clearly define variable names you are using and units. Write out the governing equations. Then set out your hand calculation section in your lab book with plenty of space so it is legible. Remember, analysis in your lab book is an exploration. You are trying to find out something about the phenomena you are observing. Often this analysis informs the next experiment or measurement you do. Documenting your analysis is as important as documenting your raw data.

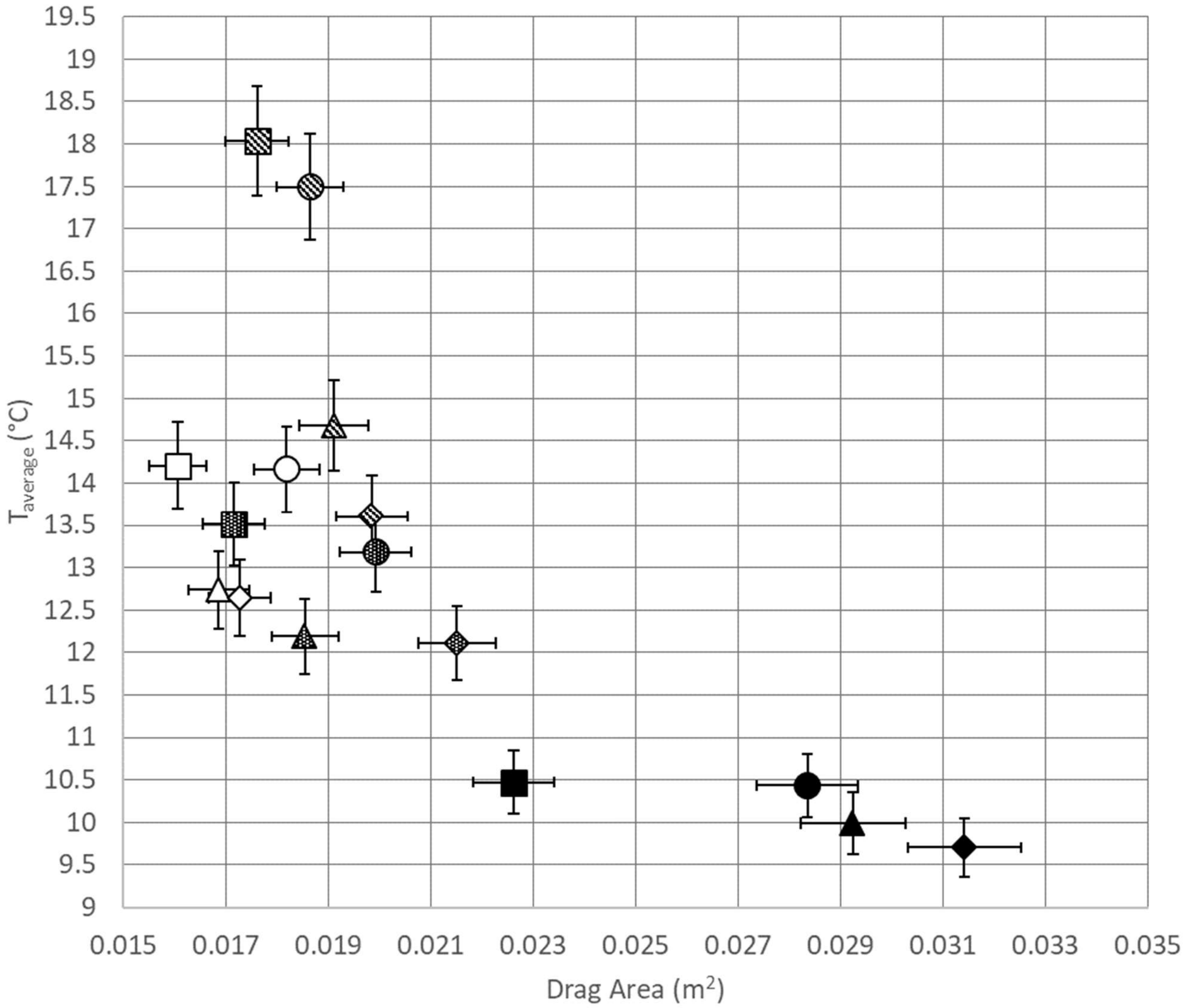
Graphs

Organise data or analysis results according to the phenomena you are trying to understand. In your lab book, make a quick hand plot of the data or results to see if your results are making sense. Again, lab book analysis is usually part of the investigation process and helps to inform the next procedure or verifies that you have done the test correctly. You will make neater, more accurate plots using a computer as well and paste those into your lab book. *Always* put a title, axis labels and units on your graphs. Always re-format Excel default graphs into scientific format.

A *bar graph* compares values across categories. The x-axis has discrete "bins" for the independent variable. The y-axis depicts the values, number of occurrences, totals, averages etc. for each category.

A *pie chart* is used to show the relative percentage or contribution of each item to the whole.

A *scatter plot* is used to plot data that should have a functional relationship, Q = *f*(x), with the independent variable, x, on the x-axis. Only connect the data points with lines if you are sure that the phenomenon has the values along the line. Normally, you plot the data points as discrete points with error bars and then you plot a trend line or curve which shows the expected functional relationship. This is the type of plot most often used in fluid mechanics. The plot below is from a peer-reviewed journal paper (Underwood et al., 2019) which compared several ventilation hole options in a bicycle helmet by plotting the temperature of the head (vertical axis) i.e. the comfort, against the drag area (drag coefficient times cross sectional area) (horizontal axis). There is some scatter in the data, as the relationship between drag area and temperature is complex, but broadly there is a relationship: low drag helmets were hot to wear. There was uncertainty in both measurements, shown here as **error bars.** Each point has horizontal lines (horizontal error bars) extending to the right and left by the uncertainty in drag area. Each point has vertical lines extending up or down by the uncertainty in temperature (+/-0.5 °C). Always plot error bars, unless they will be smaller than the shapes used to mark each point. This one plot tells us what data was collected, and how uncertain it was, in one package.



<u>Graph formatting:</u>
The default formats that Excel provides are not very engineering for scientific graphs. You will have to tune the appearance of any graphs you make in Excel.

Engineering Presentation of Data

- No grid lines unless it helps to communicate the specific information
- No fill or background colour on the graph
- No top or right hand border on the graph space unless it is an axis
- Logical tick mark spacing and readable fonts on the units

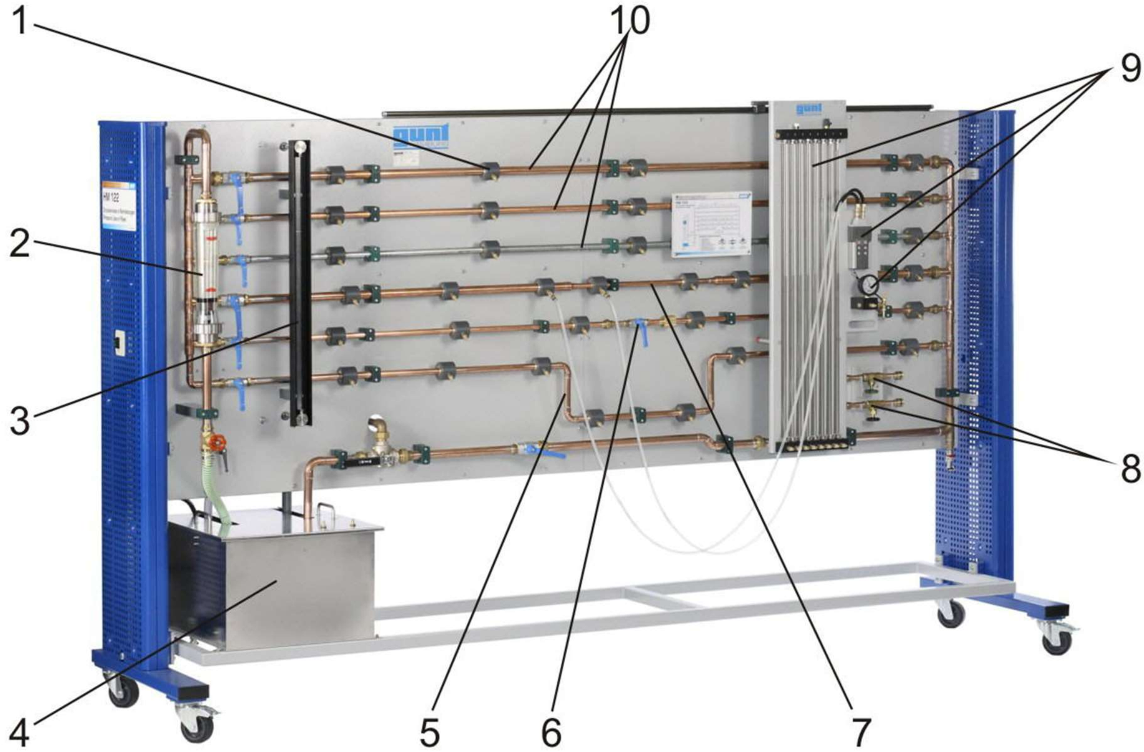
- Data points: best are small black circles, small black diamonds, small black squares, small black x’s
- Error bars indicating the uncertainty range in the dependent variable
- Do not connect data points from experiments or from discrete calculations unless you are sure they are related
- Only use a trend line that is a model of the phenomenon from physical reality (e.g. don’t just use the “trend line” function for a polynomial unless the expected behaviour $y = f(x)$ is indeed polynomial).
- In general we don’t put a box around the graph
- Don’t use a legend unless it is necessary
- Use a solid line for known functions, and dashed lines for expected or guessed functions.

If using MATLAB or Python, make sure the text is in a large enough font. The default font size is often too small.

3. LAB INSTRUCTIONS

LAB A PART I: PRESSURE AND FLOW MEASUREMENT

The purpose of this lab is to learn about flow rate measurement using the Venturi orifice plate and rotameter, and to measure pressure using an electronic pressure sensor, manometer and Bourdon gage. You will apply the rules for taking measurements, recording error and accuracy, plot data and report results with uncertainties. The GUNT HM122 lab has been engineered and built in Germany as a teaching apparatus. It has many different options for measuring flow and pressure drop across different size sections of pipe, bends, enlargements, contractions, orifice plates and valves.

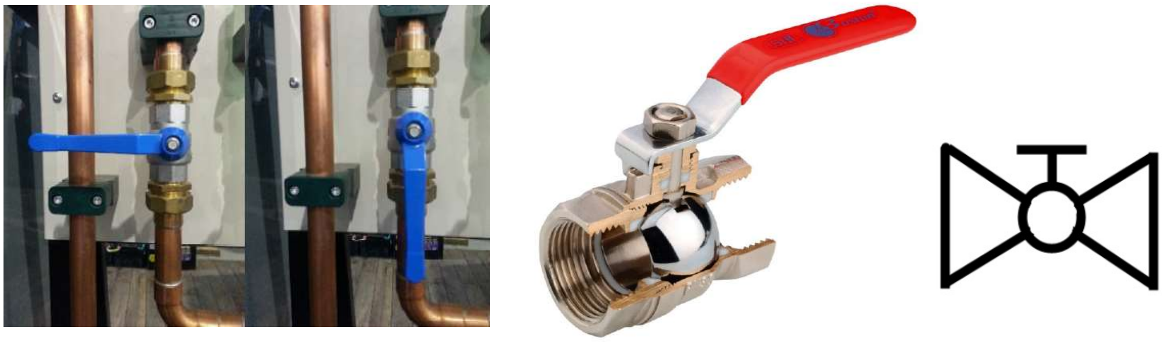


1. Annular chamber for pressure measurement, 2. Rotameter, 3. Measuring tank level indicator, 4. Tank with submersible pump, 5. Pipe section with pipe bends, 6. Pipe section with interchangeable valves and fittings, 7. Pipe section with contraction and enlargement, 8. Interchangeable valves and fittings, 9. Panel with Bourdon tube pressure gauge, electronic pressure sensor and tube manometer, 10. Long pipe sections with different diameters.

Setting Pressure Taps:

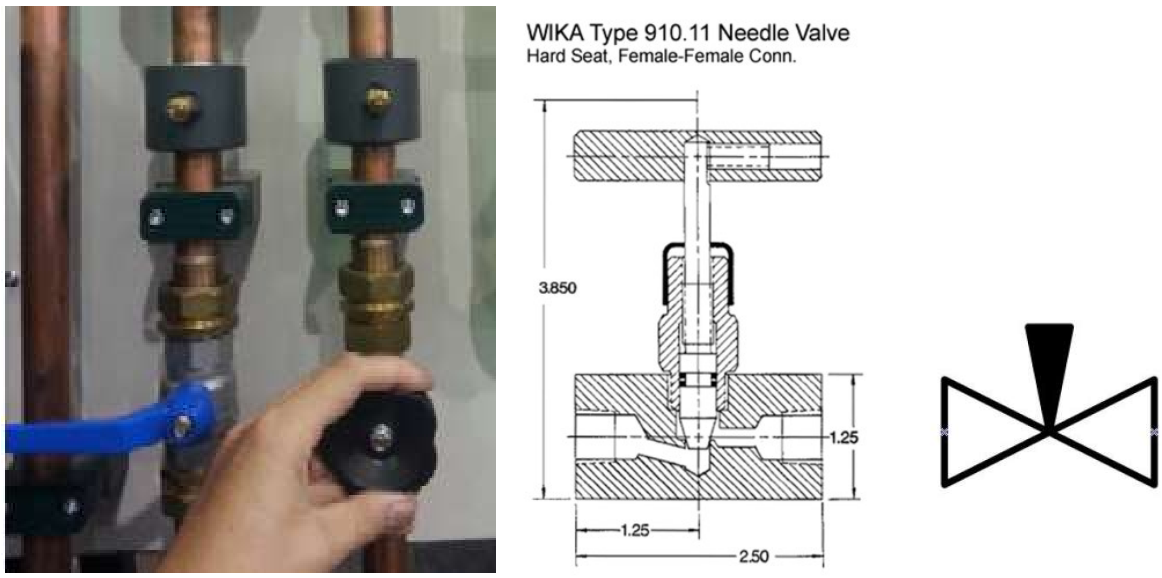
The brass fittings are self-closing and allow you to connect the manometer tubes to any tap fitting on the apparatus without leaks of the water in the pipes. Connecting the pressure taps may introduce air bubbles into the pipe. Clear bubbles by opening up the Bleeder Valves on the pressure sensor all the way until the bubbles are cleared. When all the air bubbles are gone, close the valve under the large rotameter, close both bleed valves at the same time, and turn off the pump until the electronic pressure reading falls to a stable value (a few minutes may be required). Even when settled, the electronic pressure sensor can drift over a range of +/- 0.08 mbar.

Valves:
The blue-handled valves are ***ball valves***. They are designed to fully open or fully shut off flow. They can't be used to repeatedly or reliably throttle a flow to control pressure or flow when partially open. By convention, ball valves are open when the handle is aligned with the pipe and closed when the handle is 90^{o} to the pipe.



1. Ball valves in the apparatus, 2. Cut-away view of operation of a ball valve, 3. Symbol used for ball valves in piping diagrams

The black-handled round valve under the small rotameter and the round-handled bleed valves are ***needle valves***. These valves open progressively and are used to control pressure and flow. The handle rotation raises (counter clock-wise) or lowers (clock-wise) a needle to increase or decrease the flow passage areas. You may have noticed in your experience with valves that the flow rate through valves drifts with time. You will have to carefully adjust the valve, wait for the flow to settle, then keep an eye on the rotameter and electronic pressure measurements to make sure they are stable.



1. Needle valve being adjusted. 2. Cross section drawing of a needle valve, 3. Symbol used for a flow control valve on piping diagrams.

Measurements and Units:

A water thermometer is mounted on the lower part of the rig on the main water supply pipe from the pump. You will need the temperature to determine the density of the water. Recall that density is the inverse of the specific volume. Be careful with units.

Table T-2 Properties of Saturated Water (Liquid–Vapor): Temperature Table

		Specific Volume m^3/kg		Internal Energy kJ/kg		Enthalpy kJ/kg		
Temp. °C	Press. bar	Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Sat. Liquid u_f	Sat. Vapor u_g	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g
.01	0.00611	1.0002	206.136	0.00	2375.3	0.01	2501.3	2501.4
4	0.00813	1.0001	157.232	16.77	2380.9	16.78	2491.9	2508.7
5	0.00872	1.0001	147.120	20.97	2382.3	20.98	2489.6	2510.6
6	0.00935	1.0001	137.734	25.19	2383.6	25.20	2487.2	2512.4
8	0.01072	1.0002	120.917	33.59	2386.4	33.60	2482.5	2516.1
10	0.01228	1.0004	106.379	42.00	2389.2	42.01	2477.7	2519.8
11	0.01312	1.0004	99.857	46.20	2390.5	46.20	2475.4	2521.6
12	0.01402	1.0005	93.784	50.41	2391.9	50.41	2473.0	2523.4
13	0.01497	1.0007	88.124	54.60	2393.3	54.60	2470.7	2525.3
14	0.01598	1.0008	82.848	58.79	2394.7	58.80	2468.3	2527.1
15	0.01705	1.0009	77.926	62.99	2396.1	62.99	2465.9	2528.9
16	0.01818	1.0011	73.333	67.18	2397.4	67.19	2463.6	2530.8
17	0.01938	1.0012	69.044	71.38	2398.8	71.38	2461.2	2532.6
18	0.02064	1.0014	65.038	75.57	2400.2	75.58	2458.8	2534.4
19	0.02198	1.0016	61.293	79.76	2401.6	79.77	2456.5	2536.2
20	0.02339	1.0018	57.791	83.95	2402.9	83.96	2454.1	2538.1
21	0.02487	1.0020	54.514	88.14	2404.3	88.14	2451.8	2539.9
22	0.02645	1.0022	51.447	92.32	2405.7	92.33	2449.4	2541.7
23	0.02810	1.0024	48.574	96.51	2407.0	96.52	2447.0	2543.5
24	0.02985	1.0027	45.883	100.70	2408.4	100.70	2444.7	2545.4

Rotameter: Reading is litres per hour. You will need to convert to m^3/sec using the density at the measured temperature.

Electronic pressure sensor: Reading is in mbar. You will need to convert to Pa: 1 mbar = 100 Pa

Procedure:

The objective is to measure the flowrate directly from the rotameter and calculate the flowrate across the Venturi and orifice plates using the differential pressure measurement and compare the values. You will also evaluate the pressure drop caused by the orifice plate and Venturi. You will get the flow stabilized at 600 l/h on the rotameter, then reduce the flow in increments of 100 l/h and record measurements.

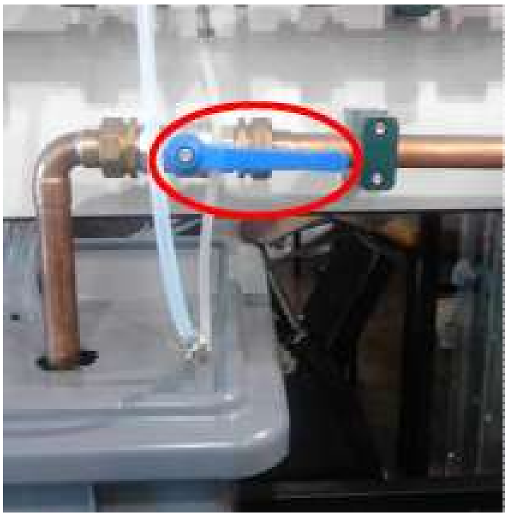
1. Explore the apparatus with your lab group. Make sure you understand all of the previous descriptions. Decide who will do what. Decide how to record measurements.

2. Find the barometer on the wall of the lab and record the atmospheric pressure on the day of your labs. You will need it later in calculations.

3. Identify the accuracy and sources of error in all of the measurements. Record the uncertainty for each instrument. Note that the fluid flowing through a needle valve will drift with time. When you start taking measurements, take at least three readings for each

measurement and record all of them. (Three is probably all you will have time for). Be careful that the pressure tap tubes are not kinked.

4. Make sure the master switch (red and yellow rotary switch) is turned off but the power is plugged in.
5. Set up the flow in the apparatus through the orifice plate.
   - Open the ball valve to the drain tank
   - Open the ball valve to the large rotameter
   - Open the valve into the horizontal orange pipe with the orifice plate
   - Close all other valves

6. Connect a pressure measurement tube to each of the two pressure ports close together on the orifice plate on the orange pipe. Connect the other ends of the measurement tubes to the electronic pressure sensor. The upstream (left hand) port should be connected to the +p port of the differential pressure sensor.

7. <u>Initiation Process:</u> Turn on at the master switch (red and yellow rotary switch). Start up the pump with the green switch and observe that the float in the large rotameter rises.

   Open the bleeder valves on the differential pressure sensor and clear all air bubbles.

   Close the valve under the large rotameter.

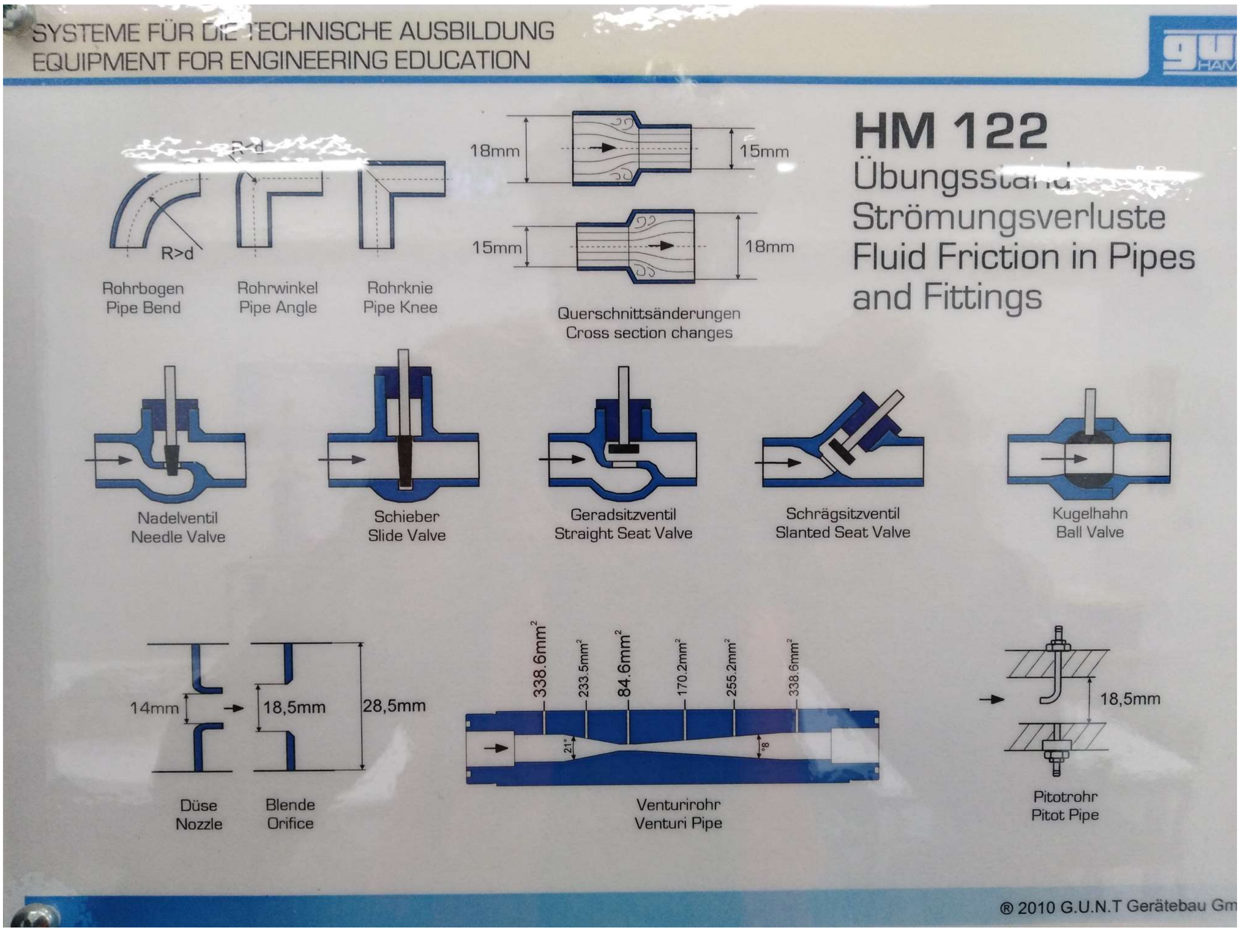
   Close both bleed valves at the same time.

Turn off the pump and allow the pressure (red readout) to fall to a stable point (this may take more than 5 minutes).

Press the RST button under the red display to zero the reading. It will continue to wander up and down. Note the uncertainty.

You are now ready to start the measurements. This is the dead state of the apparatus with no flow and no pressure difference across the orifice plate.

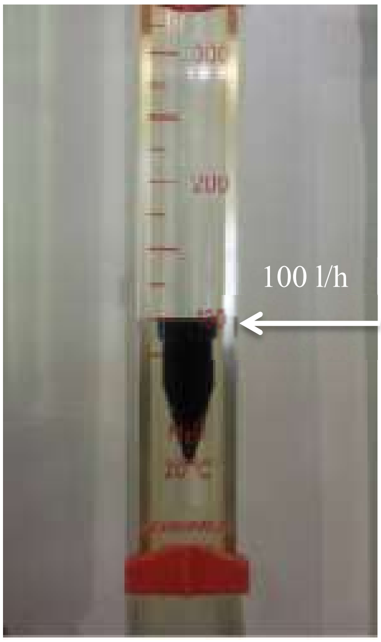
Record the pipe and orifice plate and Venturi dimensions from the plaque on the upper right corner of the GUNT apparatus (copied below).



8. <u>Measurement Process:</u>

Start the pump

Adjust the flow rate by adjusting the flow through the small rotameter with the needle valve. The reading of the small rotameter is made at the top of the float.



Adjust the flow to 100 l/h. Keep watching the float and re-adjust gently between the taking of three readings from the differential pressure reading. Note the amount of wandering which can affect repeatability. Try to keep the random uncertainty to less than +/- 0.5 mbar for the differential pressure and +/- 3% for the rotameter.

Record the water temperature (do this each time you set a new flow rate)

Increase the flow to 200 l/h and take readings.

Repeat for 300, 400, 500 and 600 l/h.

Below is an example set of readings for the orifice plate for reference. Depending on temperature and condition of the apparatus the values may vary by 20%.

Example Data with accuracy of reading recorded

Rotameter Flow Rate [litres/h] $\Delta = 15$	**Differential Pressure Reading on Orifice Plate [mbar]** $\Delta = 0.005$ **1**	**2**	**3**	**Temperature [°C]** $\Delta = 2.5$
0	0.00	0.01	0.02	25
100	0.08	0.12	0.08	25
200	0.30	0.32	0.31	25
300	0.82	0.80	0.79	26
400	1.43	1.42	1.38	26
500	2.20	2.18	2.23	26
600	3.20	3.20	3.21	26

In the above table, Δ is the uncertainty i.e. for the rotameter, any reading has an uncertainty of +/-15 litres/hour

Random Error from drift in repeated experiments

Δp= +/- 0.02 mbar ΔT = +/- 1 °C

9. Measure Pressure Loss:

   With the flow rate at 600 l/h, move the pressure taps to the taps outside the orifice plate section as shown.

10. Venturi Meter:

    Repeat steps 7 and 8 for the Venturi meter at 500 litres/hr on the rotameter. Remember to close the ball valve to the orifice section and open the ball valve to the Venturi section and to clear out any bubbles. Compare the flow reading for the Venturi to the orifice plate at the same rotameter flow.

11. Plot Data:

    Make a plot of the raw data in your lab book to quickly check that you have not had something strange go wrong. The x-axis (control variable) is the rotameter reading, the y-axis is Δp.

    Hand Calculation:

    Convert all flow rate values to m^3/s

    Carry out hand calculation of one flow rate for the orifice plate flow meter using the differential pressure measured at 500 l/h on the rotameter.

    Carry out hand calculation of one flow rate for the Venturi flow meter using the differential pressure measured at 500 l/h on the rotameter.

    Check that the rotameter, orifice plate and Venturi flow rates agree, within uncertainty.

    Convert one rotameter flow rate reading to a mass flow rate in kg/s.

    Recall: $A = \pi D^2/4$

    Orifice discharge coefficient $C_D = 0.7$

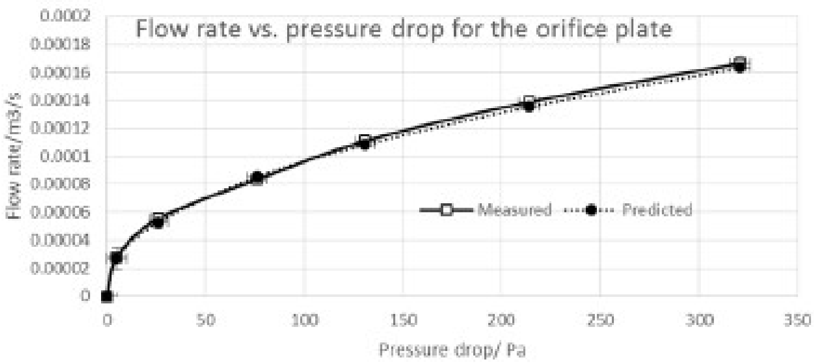
    Venturi discharge coefficient $C_D = 0.98$

    $$Q = C_D A_2 \sqrt{\frac{2(p_1 - p_2)}{\rho\left(1 - \frac{A_2^2}{A_1^2}\right)}}$$

12. Have the demonstrator stamp all of your pages completed during the lab.

13. After the Lab:

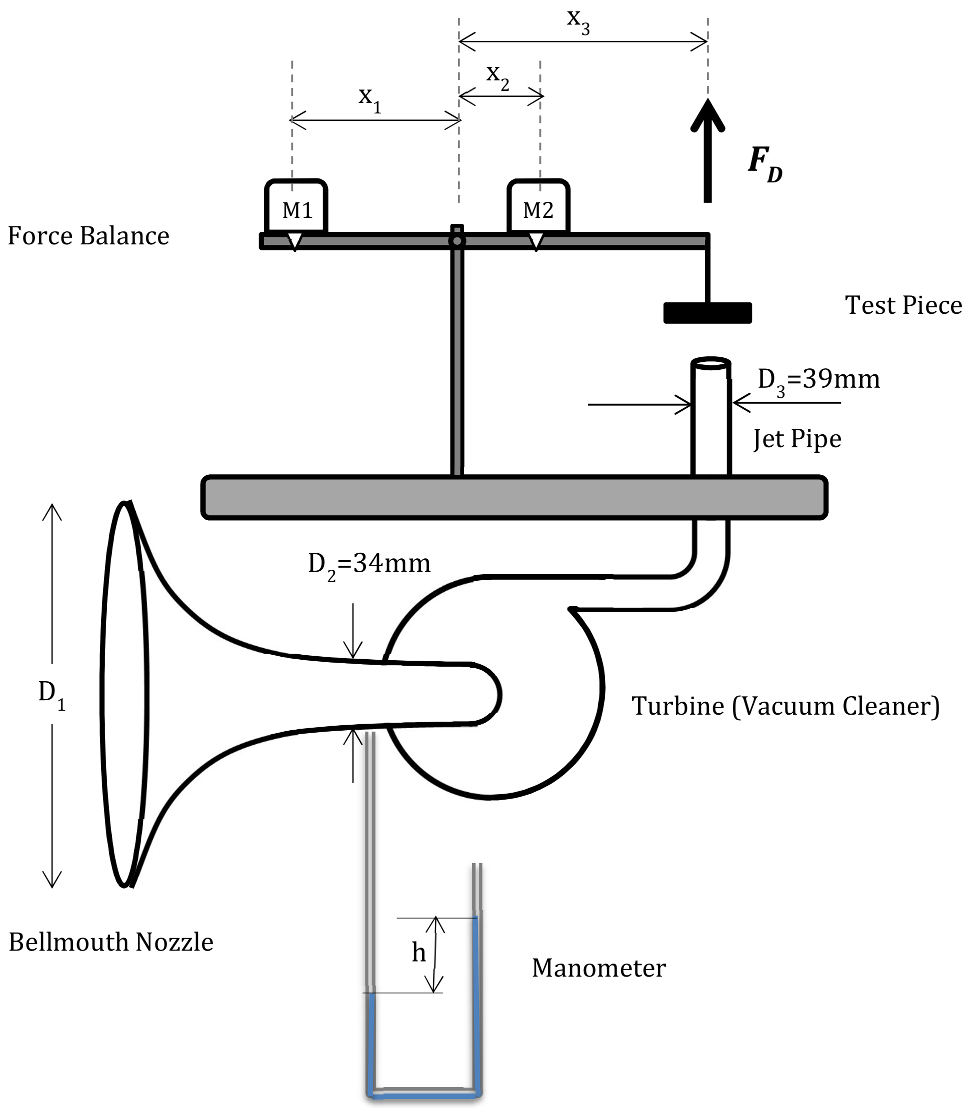
    Use Excel to carry out the calculation of the flow rates over the whole range. Estimate the error. Plot the measurement of flow rate from the measurement of pressure drop for the orifice plate as in the example below. Make a plot showing the comparison of the rotameter flow rates to the orifice flow rates. Include the error bars. Plot in the same units on both axes. Attach the plot to the lab notes in your Lab Book.



LAB A PART II: Momentum transfer and force

A jet of air impinges on an object, exerting a drag force. Momentum from the air jet is transferred to the surface of the object. Fluid momentum transfer phenomena are important in vehicle design and power generation. In this lab you will measure the drag force exerted on a flat test piece and a hemispherical test piece. The air jet is produced by the turbine from a vacuum cleaner (blowing). The resultant force will be measured using a force balance. A schematic diagram of the apparatus is shown below.

Apparatus



The bellmouth intake is a nozzle with a smooth profile that has low viscous pressure losses. The inlet pressure is atmospheric pressure and inlet velocity can be assumed to be zero. The nozzle outlet pressure is measured by a differential manometer referenced to atmosphere. The nozzle outlet diameter is known, so the flow rate can be measured at this point using the definition of mass flow and the balance of momentum for an incompressible flow:

$$\dot{m} = \rho A V$$

You can also use the **Bernoulli Equation:**

$$p_1 + \frac{1}{2}\rho V_1^2 + \gamma z_1 = p_2 + \frac{1}{2}\rho V_2^2 + \gamma z_2$$

Where p_1 is the pressure at the entrance to the bellmouth, V_1 is the magnitude of velocity at this point, p_2 is the pressure at the throat of the bellmouth, and so on.

You will also need the continuity equation with no temperature change (hence no density difference), to calculate the velocity V_3 at the exit of the jet pipe:

$$A_2 V_2 = A_3 V_3$$

$\dot{m}$ = mass flow [kg/s]
p = pressure [Pa]
ρ = density [kg/m^3]
V = velocity [m/s]
z = height [m]
$\gamma = \rho g$ [kg/m^3][N/kg]

Force Balance:
The mass M_1 is used to zero the force balance with just the test piece and the arm prior to starting the air jet. Mass M_2 is used to balance the force exerted on the arm by the drag of the air jet on the test piece. The force balance is achieved when M_2 is positioned to level the balance arm. The balance of the moments is:

$$M_2\, g x_2 + W x_4 = M_1\, g\, x_1 + \boldsymbol{F_D}\, x_3$$

Where Wx_4 is the moment of the arm about the fulcrum with the test piece but with the air jet off. If we first place the mass M_1 to balance the arm and test piece, then $Wx_4 = M_1\, g\, x_1$ and the drag force can be evaluated by solving:

$$\boldsymbol{F_D} = M_2\, g\, (x_2 / x_3) \quad \text{(this is the experimental value of drag)}$$

Note: Make your own measurement to verify x_3 = 350mm

Momentum Transfer:
The momentum equation is a vector force balance:

$$\boldsymbol{F} = \dot{m}(\boldsymbol{V_3} - \boldsymbol{V_4}) \quad \text{(theoretical value of drag)}$$

This can be used to estimate the maximum force transferred under idealised conditions (as per the text book Figure on the right). From the previous determination of the flow rate and the pipe diameters, and being careful to use the air density at the temperature measured, you can make an estimate of the air velocity in the jet. The jet pipe is slightly larger (D_3=39 mm) than the throat where mass flow rate was determined, and the temperature of the air, and the density are different. Use Bernoulli and the continuity equation to work out the unknown jet velocity and flow rate from the known bellmouth conditions and the pressure and temperature measurements.

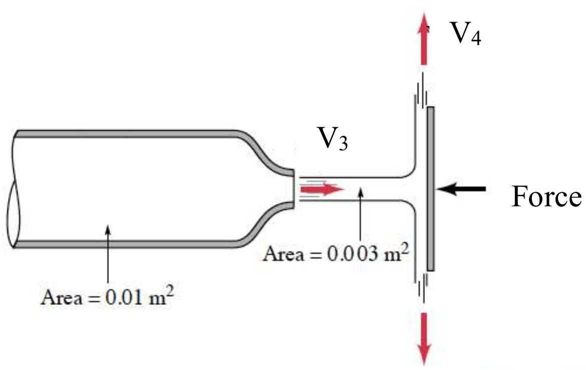


Figure P12.7

Properties:
Air can be assumed to be an ideal gas with a specific gas constant R_{air} = 287 $Jkg^{-1}K^{-1}$

Sources of Error:

- The bellmouth and the tubes all have some viscous losses. A well designed, clean bellmouth typically has a discharge coefficient of about $C_d \sim 0.98$. You can use this to improve your estimate of the mass flow rate:

$$\dot{m} = C_d \rho_2 A_2 \sqrt{\frac{2(p_1 - p_2)}{\rho_1}}$$

- The turbine does work on the air, so the temperature of the air is different in the jet from in the bellmouth. You should use the property tables in Appendix B or the ideal gas relation to calculate the density of the air at each state.
- Units will be a potential source of mistakes if you don't carefully write units with every measurement and convert from the measurement units to the standard units for calculation. For example measurements in mm need to be converted to m.
- Don't forget to use the lab barometer to determine the atmospheric pressure, and measure the lab room temperature.
- There is friction in the balance arm pivot – it is not a perfect fulcrum, so be careful in establishing balancing points.

Procedure:

1. Discuss the procedure with your group. There are 3 flat test pieces and one hemispherical piece. Decide who will do what, and how data will be recorded. Agree on a table for recording data and what units will be used. Produce the table in your lab book.
2. Check the measurements of the bellmouth and throat and jet pipe, check that the manometer is zeroed.
3. Remove M_2 and install the smallest test piece flat disk. Adjust the height so it is about 100 mm above the jet pipe. With the jet off, balance the arm by moving M_1.
   Record the value of x_1 for the test piece.
4. Turn on the vacuum and allow time for the apparatus to come to steady state, usually about 10 minutes. Think about why you need to wait. Observe the jet temperature reading to determine when steady operation has been achieved.
   Record temperatures and pressures.
5. Adjust M_2 until the force arm is balanced, record the measurement of x_2 for the test piece. Use the tuft wand to investigate the flow streamlines.
6. Repeat the procedure for the test piece at three heights, 100 mm, 180 mm and 260 mm.
7. Repeat the procedure for the two other flat test pieces.
8. Repeat the procedure for the cup test piece at just one height of 100 mm.
9. Record the uncertainty with each measurement.
10. Carry out a calculation of the experimental and theoretical force on the small flat test piece by hand for the 3 heights and check with your lab group and the demonstrator.
11. Carry out the calculation for all of the test pieces at 100 mm.
12. Make a graph in your lab book showing the observed trends in force.
13. Have the demonstrator stamp all of your pages completed during the lab.
14. After the lab:
    a. calculate the theoretical drag force for all measured conditions
    b. plot this on a new graph with the experimental drag force values, including error bars

c. write a brief (max. 10 sentences) about the possible reasons for any difference between these and the experimental drag force values.

LAB B: DIMENSIONAL ANALYSIS AND BOUNDARY LAYER CONCEPT

This assignment expose you to some of the techniques routinely used by engineers to tackle practical problems. These include modelling a problem using dimensional analysis to allow the use of scale models, and using experiment to obtain a qualitative description of the phenomena involved and relevant results.

Problem statement:

A rifle bullet manufacturer wishes to estimate the drag on his bullets which can be approximated as 5 mm diameter spheres. The bullet initial velocity is 300 m/s. Your task is to design an experiment to evaluate this drag. At your disposal, you have:

1. Wind tunnel facilities capable of producing uniform flow conditions in the range 7.0 m/s to 50 m/s. Each team will have a 25 minutes exclusive access to the wind tunnel under the close supervision of a Teaching assistant. **You must read and comply with the instructions for the safe operation of the wind tunnel facilities (see Appendix B).**
2. A 6-axis force balance.
3. 3 spheres with diameters 50mm, 202mm, and 307mm (all measurements to +/-1mm) fitted with rods (called ‘stings’) so that they can be mounted to a load cell for measuring the drag force.
4. A bare rod with no sphere. Measuring the drag of this and subtracting it from the sphere drag gives you the drag of an isolated sphere with no rod attached.
5. A spreadsheet (located on the ENME 314 LEARN page, in the Lab section) for converting the drag measurements into drag coefficients, and making corrections for conditions inside the wind tunnel, is available. This spreadsheet also contains some standard data for the drag coefficient of spheres, against which you can compare your calculated values. The standard data is for isolated spheres (no sting). This is a valuable check that you have entered your data correctly.
6. A smoke generator for visualization purposes.

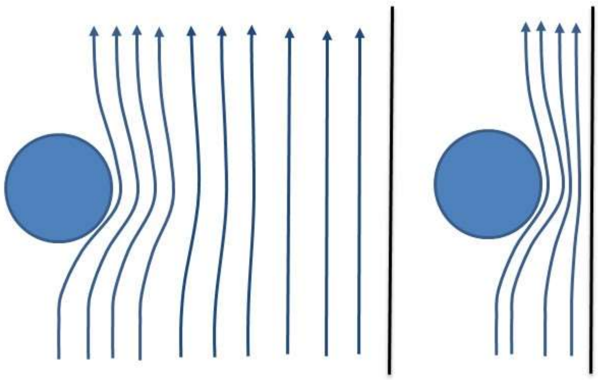
Notes on wind tunnel theory:

The wind tunnel has a fixed model (the test sphere) and a moving fluid (air). You are using it to simulate a moving object (the bullet) in a stationary fluid (atmospheric air, making a simplifying assumption it is stationary). The two scenarios are different. However the data from the wind tunnel can be used to predict (or model) what will happen with the bullet projected into stationary air if the following conditions are met:

- There are inertial reference frames (i.e. we can have fixed fluid and moving object, or vice versa: switching around may change the sign of the forces, but not their magnitude). This condition is met.
- For simplicity in preliminary tests the rifle bullet may be approximated as having a spherical shape. The test models are also spheres providing **geometric similarity**. The test models, however, can be scaled up or down in size depending on the test facilities capabilities and prototype/model manufacturing specifics. Other types of similarities have to be met as well for the modelling test to be valid to represent the real-life scenario.
- The Reynolds and Mach numbers are the same for both the bullet in air and for the sphere in the tunnel. Meeting these conditions means there is **dynamic similarity**. You should ascertain that this condition is met. A Mach number of <0.3 indicates that there are no significant compressibility effects. Discuss whether there will be compressibility effects.

- The streamlines (flow pattern) are the same in both wind tunnel and around the bullet (**kinematic similarity**). This condition is only partially met because:
  - Although both test spheres and instrument package are smooth spheres, the test spheres have a rod attached, which the instrument package does not. The rod (called a sting) has a drag of its own which must be measured and subtracted.
  - The wind tunnel has walls near the test spheres. The bullet does not. This changes the flow pattern in the wind tunnel as the flow must accelerate to pass between the test spheres and the wall (see figure below). This changes the pressure on the sphere face and hence the drag. This effect is called "solid blockage" as the solid model partially blocks the wind tunnel. The wake behind the sphere also changes the flow pattern and hence the pressure distribution on the sphere. This effect is called "wake blockage".

Sting drag and the two blockage effects can be corrected for.



Left: Sphere in the free flow away from the solid walls. Right: Sphere in the wind tunnel next to a solid wall. Acceleration of the flow between the sphere and the tunnel walls leads to blockage effects.

Sting drag correction:

The item you measure the drag of is the (sphere + rod). It has a drag coefficient $C_{D(s+r)}$ and a frontal area $A_{(s+r)}$ equal to the frontal area of the sphere plus the frontal area of the rod. You calculate the product $C_{D(s+r)}A_{(s+r)}$ (called the drag area) so:

$$C_{D(s+r)}A_{(s+r)} = \frac{F_{drag,sphere+rod}}{\frac{1}{2}\rho_{air}V_{air}^2}$$

You separately measure the drag of the rod alone and calculate its drag coefficient $C_{D(r)}$ similarly, using the frontal area of the rod $A_{(r)}$.

Now you can subtract the drag area of the rod from the drag area of the (sphere + rod), and divide by the area of the sphere alone to find the drag coefficient of the sphere alone:

$$C_{D(s)} = \frac{C_{D(s+r)}A_{(s+r)} - C_{D(r)}A_{(r)}}{A_{(s)}}$$

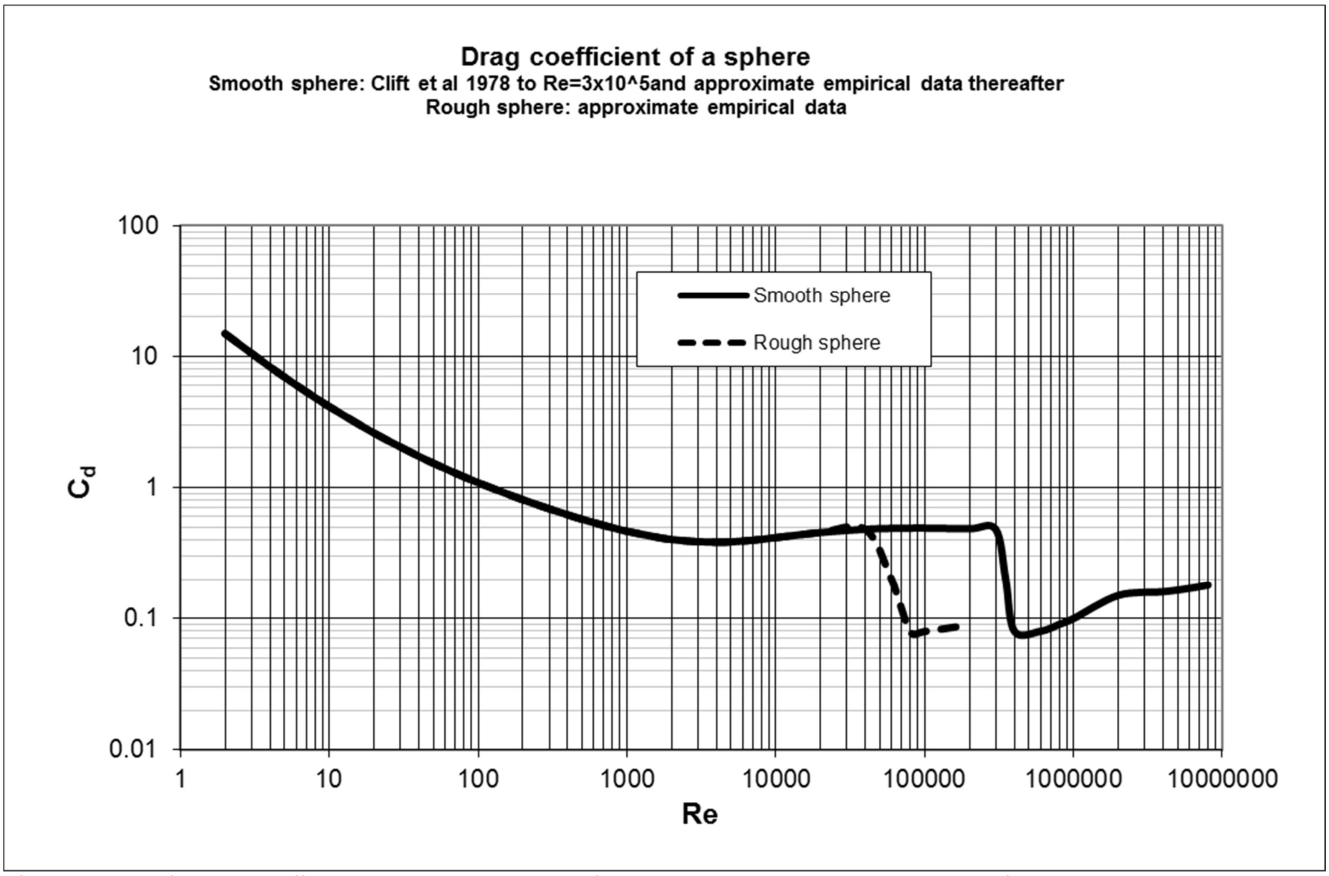
This completes the sting drag correction.

Solid and wake blockage corrections:

These use empirical formulae determined by Cooper, Merkcer and Wiedemann (1999) which are described in (and coded into) the spreadsheet you have been supplied with.

Standard sphere drag data

As with flat plates, sphere drag has been measured in different experiments, using falling spheres, wind tunnels, water tunnels and other tests. As there is geometric and dynamic similarity, all this data lies on a single curve if drag coefficient is plotted against Reynolds number. An empirical function has been fitted to the smooth-sphere data collected by Clift, Grace and Weber (1978). This function is valid up to Re < $3x10^5$. Figure 4 is a combination of their function and empirical data for greater Reynolds numbers. Also shown in the figure below is fictional, but representative data for a rough spheres. Rough spheres have the sudden drop in drag coefficient (the 'drag crisis') at lower Reynolds numbers than smooth spheres. Not all rough spheres are the same: unless the relative roughness (roughness height/diameter) is the same, different roughnesses give different drag coefficient curves. The smooth sphere data is also in the supplied spreadsheet.



Standard data for drag coefficient vs. Reynolds number for smooth spheres, and empirical data for rough spheres. There are no error bars as the uncertainty of the measurements was less than the thickness of the line on the graph (except in the case of the rough sphere data, which is made up!).

At the wind tunnel:

1. Record the atmospheric pressure and air temperature inside the tunnel at the time of your test. You will need these to determine the air density and viscosity (formulas are coded into the supplied spreadsheet). Tabulated physical properties of air can be found in Appendix B.
2. Chose the spheres and calculate test velocities by applying the principles of dimensional analysis.

3. Mount each of the spheres in turn, bring the tunnel to a steady operating speed using the wind tunnel LabVIEW control programme, and measure the drag force. Record and save the force balance data using the LabVIEW programme.
4. The log .txt file has three columns: time (seconds), Pitot probe measured velocity (m/s), drag force (N), side force (N), lift (N) and moments. Keep the length of exposed sting the same for all tests.
5. Average the reading over a few seconds and note any fluctuations.
6. Measure the drag of the sting with no sphere attached.

Assessment

Use the supplied spreadsheet (can be downloaded from ENME314 LEARN page) to calculate the drag coefficient of the spheres, correcting for sting drag, solid and wake blockage.
Use the measured drag, or the standard drag coefficient data to estimate the drag on a bullet. Estimate how far it will travel if fired horizontally from 1.8 m above level ground, given that it weighs 0.5g (note: some programming may be required).
Write a report, of no more than 6 sides of A4, at a font size of no less than 10 points, with at least 10 mm margin on all four edges.
The report must include:

1. The course code, lab title, your name, student number, and the date you attended the lab. This does not need to take up a whole page. Do not make a separate title page.
2. A brief description of the apparatus and procedure. Justify the choice of operating conditions.
3. Describe the uncertainty and variability in each measurement.
4. Plots of your corrected drag coefficient and the standard data (over some relevant range of Reynolds numbers). You can use the plots in the Excel sheet supplied, adapting them if you wish. Make sure the plots are interpretable when printed in black and white.
5. Write a commentary on the agreement (or otherwise) between your drag coefficients to standard data. Consider the reasons for any discrepancy. These might include, for example, measurement uncertainty, or any deviation from similarity, imperfections in the use of the sting, wake and solid blockage corrections, or some assumption that has been made being imperfect.
6. Describe the method and results of your calculation of the distance the bullet will travel. State the assumptions made and the effect of these on bullet flight.
7. Discuss the uncertainty in your bullet distance calculation given the limitations in the input data.

Write simply and clearly. One idea per sentence.
Upload your report as in PDF format to the Lab B report upload activity on the Learn page.

References

Clift R, Grace JR and Weber ME (1987), “Bubbles, drops and particles”, Academic Press

Cooper KR, Merkcer E and Wiedemann J (1999), "Improved blockage corrections for bluff bodies in open and closed wind tunnels", Wind Engineering into the 21st Century, Larsen, Larose and Livesey (eds) 1999, Balkema, Rotterdam, ISBN 90 5809 059 0

Underwood L., Kiffer T., Sran H., Jay K., Villien A., Kabaliuk N. and Jermy M., (2019) “Simultaneous assessment of thermal comfort and aerodynamic drag of cycling helmets as a function of ventilation hole configuration”, special edition “Fluid mechanics in sport” of Proc IMech E part P J. Sports Eng. and Tech. https://journals.sagepub.com/doi/10.1177/1754337119852538

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Appendix A: Instructions for the Safe Operation of Wind Tunnel Facilities

These instructions refer to the safe operation of both the Closed-Circuit wind tunnel (CCWT) and Open-Circuit wind tunnel (OCWT) in E120 Aero lab, Mechanical Engineering lab wing.			
All operators must be inducted by Dr Natalia Kabaliuk (Projects Engineer in charge of the Aerodynamics and Optics Laboratories) before commencing and preparatory work leading to tests involving either wind tunnel.			
Action #	Activity/action to be completed	Responsibility	Due date
1	Permission must be obtained from Dr Kabaliuk each time before working on or operating the wind tunnels.	Everyone	Ongoing
2	The dates and times of the planned tests must be clearly communicated to Dr Mohs.	Everyone	Ongoing
3	Check that the wind tunnel has no other operators or setting up/maintenance work in progress.	Everyone	Ongoing
4	Check that the wind tunnel flow path has no loose tools or unsecured parts. All models and instruments must be securely mounted.	Everyone	Ongoing
5	The tunnel traversers must be locked in place or powered to prevent movement in the airstream.	Everyone	Ongoing
6	Minimise loose cabling within the tunnel and over the laboratory floor. Cables and hoses must NOT be laid across the stairway unless they are secured in a manner that is safe for users of the stairway.	Everyone	Ongoing
7	All wind tunnel access doors must be securely closed.	Everyone	Ongoing
8	Do NOT exceed 10 kg load onto the six-axis force balance and do NOT apply impact loads.	Everyone	Ongoing
9	Do NOT connect the pressure measuring manometers to high pressure mains air supply or blow into the pressure tubing to avoid damaging them or other pressure sensors.	Everyone	Ongoing
10	Operate at or below any specified air speed limit. These limits are to control noise levels in adjacent laboratories. The current speed limit for the CCWT is 50 m/s.	Everyone	Ongoing
11	Typical noise levels near both wind tunnels do NOT exceed 80dB which is below the safe limit of 85dB. However, operators using the tunnel at high speed for prolonged periods are recommended to use adequate ear protection at all times. Ask for ear defenders if require.	Everyone	Ongoing
12	Eye protection (safety spectacles) must be worn when entering the airstream, placing the head in the airstream or working at the exit of the OCWT.	Everyone	Ongoing
13	Appropriate eye protection may be required when using UV or laser light for flow visualisation.	Everyone	Ongoing
14	Specific permission must be obtained for the use of smoke visualisation techniques in the wind tunnels to avoid triggering the laboratory smoke alarms and to keep the oil deposition in the wind tunnels to a minimum.	Everyone	Ongoing
15	Do NOT enter the wind tunnels in the vicinity of the fans without specific permission and adequate isolation of the electric power to the fans, to prevent the fans from starting accidentally.	Everyone	Ongoing
16	Do NOT access wind tunnel electrical switchboxes.	Everyone	Ongoing
17	Wind tunnel PC should be dedicated to wind tunnel related use only.	Everyone	Ongoing
18	Do NOT remove wind tunnel equipment without authorisation.	Everyone	Ongoing
19	You must clean your work area daily.	Everyone	Ongoing

Appendix B: Properties of pure water and air

Water

Temperature deg C	Density kg/m3	Dynamic viscosity μ Ns/m2	Kinematic viscosity ν m2/s	Bulk modulus B Pa	Surface tension σ N/m	Vapour pressure kPa
0	999.9	1.792E-03	1.792E-06	2.04E+09	7.62E-02	0.61
5	1000.0	1.519E-03	1.519E-06	2.06E+09	7.54E-02	0.872
10	999.7	1.308E-03	1.308E-06	2.11E+09	7.48E-02	1.13
15	999.1	1.140E-03	1.141E-06	2.14E+09	7.41E-02	1.6
20	998.2	1.005E-03	1.007E-06	2.20E+09	7.36E-02	2.34
30	995.7	8.010E-04	8.040E-07	2.23E+09	7.18E-02	4.24
40	992.2	6.560E-04	6.610E-07	2.27E+09	7.01E-02	7.38
50	988.1	5.490E-04	5.560E-07	2.30E+09	6.82E-02	12.3
60	983.2	4.690E-04	4.770E-07	2.28E+09	6.68E-02	19.9
70	977.8	4.060E-04	4.150E-07	2.25E+09	6.50E-02	31.2
80	971.8	3.570E-04	3.670E-07	2.21E+09	6.30E-02	47.3
90	965.3	3.170E-04	3.280E-07	2.16E+09	6.12E-02	70.1
100	958.4	2.840E-04	2.960E-07	2.07E+09	5.94E-02	101.3

Air

Temperature (°C)	Density, ρ (kg/m^3)	Specific Weight[b], γ (N/m^3)	Dynamic Viscosity, μ (N·s/m^2)	Kinematic Viscosity, ν (m^2/s)	Specific Heat Ratio, k (—)	Speed of Sound, c (m/s)
−40	1.514	14.85	1.57 E − 5	1.04 E − 5	1.401	306.2
−20	1.395	13.68	1.63 E − 5	1.17 E − 5	1.401	319.1
0	1.292	12.67	1.71 E − 5	1.32 E − 5	1.401	331.4
5	1.269	12.45	1.73 E − 5	1.36 E − 5	1.401	334.4
10	1.247	12.23	1.76 E − 5	1.41 E − 5	1.401	337.4
15	1.225	12.01	1.80 E − 5	1.47 E − 5	1.401	340.4
20	1.204	11.81	1.82 E − 5	1.51 E − 5	1.401	343.3
25	1.184	11.61	1.85 E − 5	1.56 E − 5	1.401	346.3
30	1.165	11.43	1.86 E − 5	1.60 E − 5	1.400	349.1
40	1.127	11.05	1.87 E − 5	1.66 E − 5	1.400	354.7
50	1.109	10.88	1.95 E − 5	1.76 E − 5	1.400	360.3
60	1.060	10.40	1.97 E − 5	1.86 E − 5	1.399	365.7
70	1.029	10.09	2.03 E − 5	1.97 E − 5	1.399	371.2
80	0.9996	9.803	2.07 E − 5	2.07 E − 5	1.399	376.6
90	0.9721	9.533	2.14 E − 5	2.20 E − 5	1.398	381.7
100	0.9461	9.278	2.17 E − 5	2.29 E − 5	1.397	386.9
200	0.7461	7.317	2.53 E − 5	3.39 E − 5	1.390	434.5
300	0.6159	6.040	2.98 E − 5	4.84 E − 5	1.379	476.3
400	0.5243	5.142	3.32 E − 5	6.34 E − 5	1.368	514.1
500	0.4565	4.477	3.64 E − 5	7.97 E − 5	1.357	548.8
1000	0.2772	2.719	5.04 E − 5	1.82 E − 4	1.321	694.8