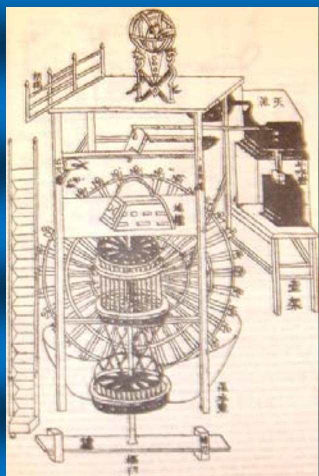
The City College of New York

HYDRAULIC ENGINEERING LABORATORY

EXPERIMENTS

FOR

CE 365, HYDRAULICS AND HYDROLOGY



Department of Civil Engineering
The City College of New York
December 2014

Experiment 1

Center of Pressure on Partially and Fully Submerged Plates

Objective

- To determine the center of pressure on a partially submerged and fully submerged plane surface.

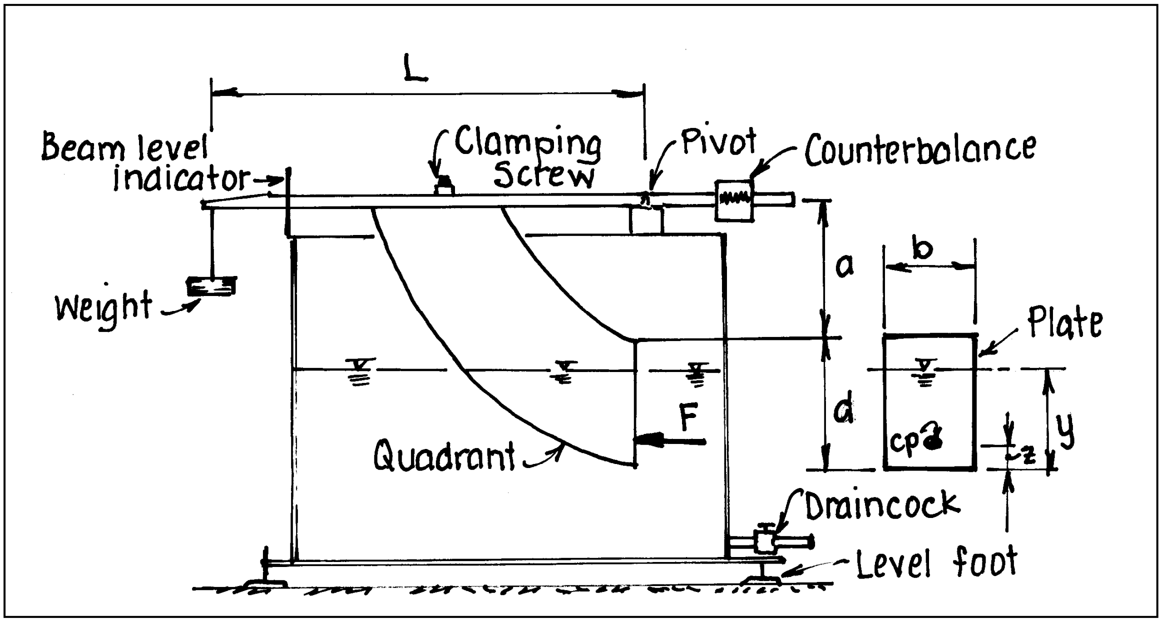


Figure 1-1 Hydrostatic Pressure Apparatus

Procedure:

1. Place the quadrant on the two dowel pins and, using clamping screw, fasten it to the balance arm.
2. Level the Plexiglas tank by adjusting the screwed feet. The level is indicated on the circular spirit level.
3. Hang the balance pan and make the balance arm horizontal by moving the counter balance weight.
4. Measure a, L, d, b as shown in Figure 1-1.
5. Close the drain cock and fill the tank with water until the water level reaches the bottom edge of the quadrant. Level the arm by moving the counterbalance weight.
6. Place 50 grams on the balance pan and slowly add water to the tank until the balance arm is again horizontal. Record the water level (y) on the quadrant and the weight on the balance pan (W = mg).

7. Repeat Step 6 for several increments placing about 50 grams on the balance pan for each step until the water level reaches the top of the quadrant end face. Repeat Step 6 one more time so that the quadrant end face is totally submerged for this last run.
8. Remove each increment of weight and allow the water to drain until the balance arm is level. Note the weights and water levels for each increment as the weights are removed.

Interpretation of Results:

You want to find the center of pressure on the plate for each reading taken during filling and draining the tank. To do this, take moments about the pivot. Thus,

$$-mg(L) + F(a + d - z) = 0 \tag{1-1}$$

in which z = the height of the center of pressure above the bottom of the plate. The force on the submerged plate is given by,

$$F = \rho g \bar{y} A \text{ with } \bar{y} = \frac{1}{2} y \text{ and } A = by \tag{1-2}$$

Therefore,

$$F = \rho g b \frac{y^2}{2} \tag{1-3}$$

Substituting,

$$-mg(L) + \left(\frac{\rho g y^2 b}{2} \right)(a + d - z) = 0 \tag{1-4}$$

Solving for z we get,

$$z = a + d - \frac{2mL}{\rho y^2 b} \tag{1-5}$$

Note that ρ = 1 gm/cm^3 or 1000 kg/m^3.

For each of the readings obtained during filling and draining the tank calculate the height above the bottom of the plate of the center of pressure (z) and plot the calculated values of z against y. Fit a straight line to the data.

Questions:

1. What is the slope of the straight line?
2. How far above the bottom of the plate should the center of pressure be?
3. Theoretically, what should the value of the slope be? Did you get this value? If not, why not?
4. If the plate had been a isosceles triangle with its base at the bottom, what would the theoretical slope of the line be?

Data:

Water temperature=

a= 10.2 cm; L=27.5 cm; d= 10.0 cm; b=7.5 cm

Tank Filling		Tank Draining	
m (gm)	y (cm)	m (gm)	y (cm)

Experiment 2

Fluid Friction- and Local Losses for Water Flow through Pipes

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Objective:

- To determine fluid friction coefficient and Reynolds' number for flow of water through a pipe having smooth bore.
- Head loss due to fluid friction and velocity for flow of water through smooth pipes.
- Head loss coefficients due to a number of different pipe fittings such as valves, flow devices, turns, and pipe size changes.

Theory:

For a circular pipe flowing full, the head loss due to friction may be calculated from the formula:

$$h = \frac{f_D L V^2}{2gD}$$

L is the length of the pipe between tappings, D is the internal diameter of the pipe, V is the mean velocity of water through the pipe in m/s, g is the acceleration due to gravity in m/s^2 and f_D is the Darcy pipe friction coefficient.

Reynolds' number, Re, can be found using the following equation:

$$Re = \frac{\rho V D}{\mu}$$

where μ is the dynamic viscosity and ρ is the density.

In addition to the spatially continuous head loss due to friction, local head losses occur at changes of cross section (Ex.: elbows, bends, contractions, expansions or valves). These local losses are referred to as 'minor' losses since in long pipelines their effect may be small in relation to the friction loss.

The loss coefficient for sudden expansion is:

$$h_L = \left(\frac{V_1^2 - V_2^2}{2g}\right) = K_L\left(\frac{V_1^2}{2g}\right), K_L = (1 - \frac{A_1}{A_2})^2$$

The loss coefficient for sudden contraction is:

$$K_c = \frac{h_L}{\left(\frac{V_2^2}{2g}\right)}$$

h_L = Head loss (m)

V_2 = Mean velocity in downstream section of Diameter D_2 (m/s)

g = Acceleration due to gravity (m/s^2)

The loss coefficient for pipe bends is:

$$K_b = \frac{h_b}{\left(\frac{V_2^2}{2g}\right)}$$

h_b = Loss of head in pipe bends (m)

V_2 = Mean velocity (m/s)

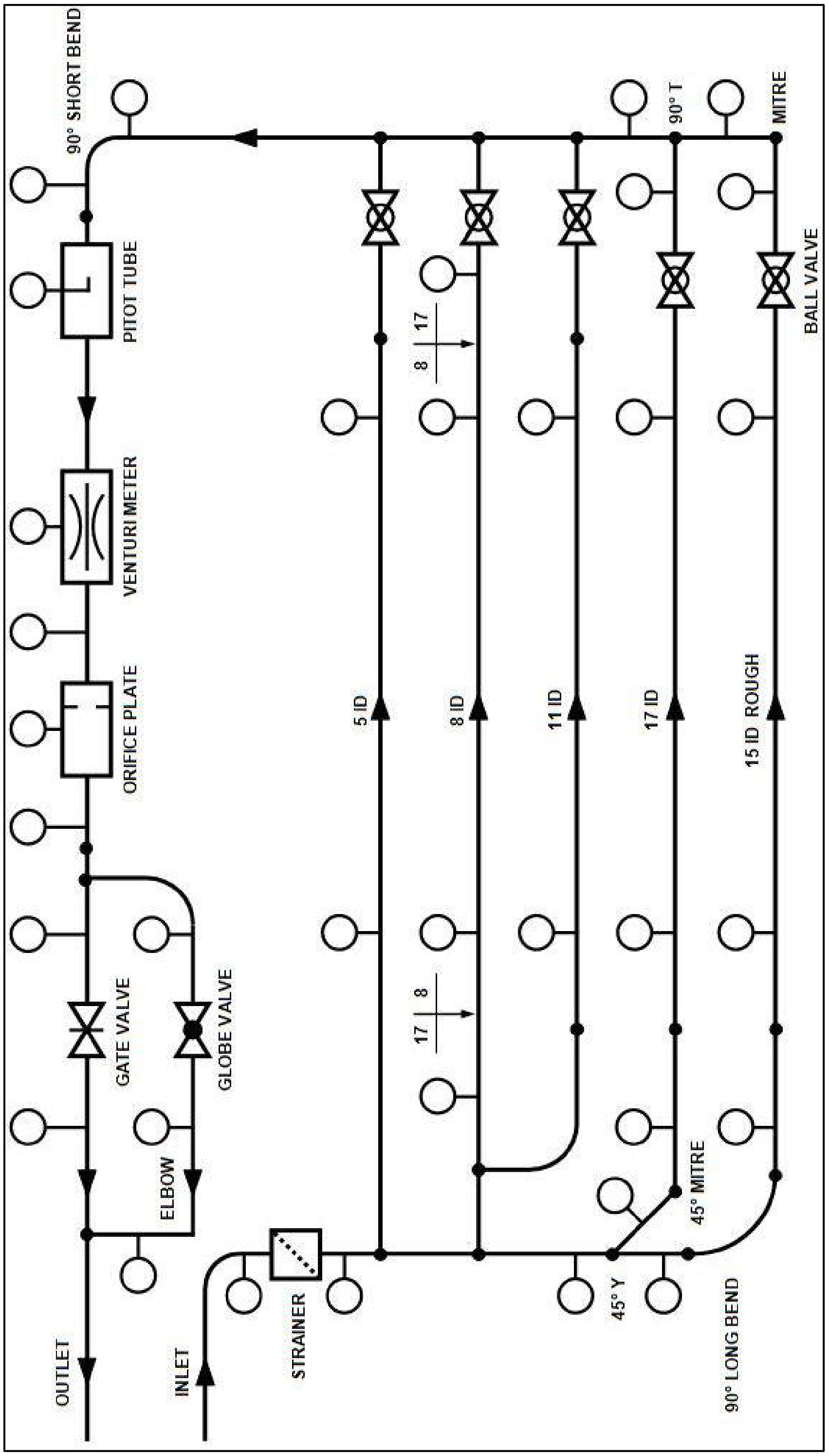
g = Acceleration due to gravity (m/s^2)

Requirements for parallel pipe flow:

$$h_{L1} = h_{L2}$$

$$Q_T = Q_1 + Q_2$$

Schematic:



Test Pipe Diameters:

1. 19.1mm x 17.2mm
2. 12.7mm x 10.9mm
3. 9.5mm x 7.7mm
4. 6.4mm x 4.5mm
5. 19.1mm x 15.2; rough

Distance between tappings

1.00m

Procedure:

1. Prime the pipe network with water. Open and close the appropriate valves to obtain flow of water through the required test pipe.
2. It is important to expel any air which may be trapped in the pipe of the pressure meter before taking readings. Close the Globe valve and partly close the Gate valve. Connect the meter tubes to a convenient pair of tappings (uppermost pipe) and switch on the pump. Carefully undo one of the nuts holding the tubing to the pressure meter until liquid is expelled from the joint. Bleed the tube to expel any air. Tighten the nut and repeat for the other tube.

   When taking the readings it is important also that the meter is zeroed first. With the pump still on, close the outlet valves and then close the control valve to leave the system at a high static pressure. When the reading on the meter has stabilized, press the zero button to reset the meter.
3. a) **<u>Older Unit</u>**: Measure flow rates using the volumetric tank
   b) **<u>Newer Unit</u>**: Read flow rate from interface and also use the V-tank for lower flow rates to have a 2^{nd} reading.
4. Take readings at **<u>three different flow rates</u>** for each pipe, altering the flow using the control valve on the hydraulics bench.
5. Major Head losses measurements:
   - Measure the internal diameter of each test pipe sample.
   - Measure head loss between the tappings using the
     a) **<u>Older Unit:</u>** hand-held meter for each pipe reading off deltaH, the head drop
     b) **<u>Newer Unit:</u>** using the pressure sensors (computer screen)
   - Using the corresponding pipe lengths estimate f_D using Darcy-Weisbach equation.
   - Find f_D using Moody diagram.
   - Obtain readings on all **four smooth** test pipes (do not use the rough pipe at the bottom of the set up).
6. Minor Head loss measurement
   - Measure head loss between the tappings on **<u>four</u>** fittings of your choice, that is one each from the following groups (refer to above Schematic for location):
     - valves (Gate, Globe or Ball)

- devices (orifice, Venturi, Pitot)
- turns (90 short bend, 90 long bend, 90 mitre, 90-T, 45 mitre, 45-Y, elbow)
- size-change (contraction or expansion on any of the pipe sections)

a) **Older Unit**: the portable pressure meter (again the head drop deltaH)
b) **Newer Unit**: the pressure sensors (computer screen)

Processing Results:

All readings should be tabulated. As references you can use the tables on the last section of the manual.

Results:

1. For Major losses:
    a. Plot a graph of pipe friction coefficient versus Reynolds number (log scale) for each size of pipe.
    b. Plot a graph of head loss versus velocity for each size of pipe. State if the flow is laminar, transitional or turbulent.

2. For Minor Losses:
    a. Plot a graph of $V^2/2g$ versus head loss for each fitting. Fit the curve with a straight line. Determine the value of K from the slope of the line. Compare with available data from the literature.

Data:

Table 1 - Table for Major Losses

Pipe Number	**Volume Vol [litres]**	**Time T [Secs]**	**Flow rate Q [m^3/s]**	**Pipe Diam. D [m]**	**Velocity V [m/s]**	**Reynolds Number Re**	**Measured Head Loss h**	**Friction factor f**	**Friction factor f**
			$\frac{Vol \times 10^{-3}}{T}$		$\frac{4Q}{\pi D^2}$	$\frac{\rho VD}{\mu}$		Darcy-Weisbach	Moody Diagram

Table 2 - Table for minor Losses

<table>
<tr><th>Pipe Fitting</th><th>Volume (L)</th><th>Time (secs)</th><th>Pipe Diameter 1 (mm)</th><th>Pipe Diameter 2 (mm)</th><th>ΔP (Kpa)</th></tr>
<tr><td>Minor loss 1</td><td></td><td></td><td rowspan="3"></td><td rowspan="3"></td><td></td></tr>
<tr><td>Minor loss 1</td><td></td><td></td><td></td></tr>
<tr><td>Minor loss 1</td><td></td><td></td><td></td></tr>
<tr><td>Minor loss 2</td><td></td><td></td><td rowspan="3"></td><td rowspan="3"></td><td></td></tr>
<tr><td>Minor loss 2</td><td></td><td></td><td></td></tr>
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<tr><td>Minor loss 3</td><td></td><td></td><td rowspan="3"></td><td rowspan="3"></td><td></td></tr>
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<tr><td>Minor loss 4</td><td></td><td></td><td rowspan="3"></td><td rowspan="3"></td><td></td></tr>
<tr><td>Minor loss 4</td><td></td><td></td><td></td></tr>
<tr><td>Minor loss 4</td><td></td><td></td><td></td></tr>
</table>

NOTE! The pipe diameter columns are only relevant when measuring across an expansion or a contraction. For the other three minor loss devices/sections, just use this space to identify which minor loss device/section you are sampling here. For example, you may just put down in column Pipe 1: Ball Valve, or 90 long bend, etc. This way it is clear what your target is.

Experiment 3

Verification of Bernoulli's Theorem

Objective:

- The purpose of this experiment is to illustrate Bernoulli's Theorem by demonstrating the relationship between pressure head and kinetic energy head for a conduit of varying cross-section.

Pre-Lab Setup:

1. Set up the Bernoulli apparatus on the working surface and level it.
2. Connect the supply hose to the inlet stub and tighten the hose.
3. If not already open, open the outlet valve on the Apparatus.

Tapping Position	Manometer Legend	Diameter (mm)
A	h_1	25.0
B	h_2	13.9
C	h_3	11.8
D	h_4	10.7
E	h_5	10.0
F	h_6	25.0

Note: The assumed datum position is at tapping A associated with h1

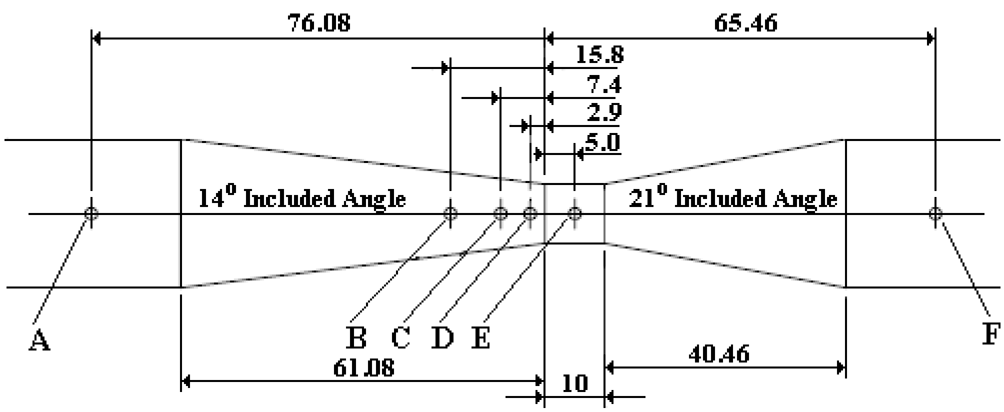


Figure 3-1 Bernoulli Apparatus

Theory:

Bernoulli's equation is derived by integrating the equations of fluid motion. Assumptions used to obtain the simplified version of the equation are that the fluid is inviscid and incompressible and that the flow is steady. Bernoulli's equation is a mathematical statement of the work-energy principle which directly corresponds to the equations of motion. This principle states that the work done on a particle is equal to the change in kinetic energy of the particle. Along a streamline,

$$\frac{p}{\gamma}+\frac{v^2}{2g}+z=const. \qquad (3\text{-}1)$$

Conservation of Mass:

For a given cross-sectional area the product of the velocity and density is proportional to the mass flow rate.

$$M=\rho Q=\rho v A_n \qquad (3\text{-}2)$$

$$v=\frac{M}{\rho A_n}=\frac{(mass\,/\,time)}{(mass\,/\,vol)\,A_n}=\frac{(vol\,/\,time)}{A_n}=\frac{Q}{A_n} \qquad (3\text{-}3)$$

$Q=vA_n$ (continuity equation for incompressible fluid)

where, M = mass flow rate,

Q = volumetric flow rate,

v = average velocity,

A_n = area normal to the direction of flow, and

ρ = mass density.

Between any two points in the flow, Inflow = Outflow. Therefore,

$$M_{in}=M_{out} \qquad (3\text{-}4)$$

$$\rho_1 v_1 A_1=\rho_2 v_2 A_2 \qquad (3\text{-}5)$$

which for an incompressible fluid becomes,

$$v_1 A_1=v_2 A_2=Q \qquad (3\text{-}6)$$

If the cross-sectional area decreases, the velocity must increase to satisfy continuity. Applying Bernoulli's equation to a flow where there is no change in elevation (*z* = constant), a decrease in velocity must be accompanied by an increase in pressure and vice versa. Bernoulli's equation expresses the conservation of energy and that the work done on the fluid shows up as a change in kinetic and/or potential energy.

The total head h_t is the addition of the static head h and the dynamic, or velocity, head h_d. In other words

$$h_t = h + h_d = \frac{p}{\gamma} + \frac{v^2}{2}$$

Procedure:

1. Readings should be taken at 3 different flow rates with long taper upstream and the total head tube fully retracted from the test-section.

2. Close the main control valve and start the pump.

3. To bleed air from the flexible connections and the manometer tubes connect a length of small bore tubing from the air bleed connection to the overflow cut-out in the side of the volumetric tank.

   Gradually close the close outlet flow control valve to increase the pressure in the test section, then open the air bleed screw until all air bubbles have been flushed from the system. When all the manometer tubes are completely full of water, close the air bleed screw then open the outlet flow control valve to give a small flow through the test section. Connect the hand air pump to the air bleed connection, open the air bleed screw then apply pressure using the hand pump until the indicated levels on the manometer are located at around the 180 or 170mm marking; this provides for a good initial level horizon. Close the air bleed valve. The manometer equipment is ready to use.

4. Take the first set of readings at the maximum flow rate possible (with all manometers reading on the backboard). The maximum volume flow rate will be determined by the need to have the maximum (h1) and minimum (h5) manometer readings both with the range of the scale. You may need to adjust the pump flow rate (on the bench) and the outflow valve (on the Apparatus) simultaneously to have this 'optimum' spread across the backboard.

5. Record the associated flow rate with a timed volume collection. This can be done on the hydraulic bench reading the water levels and timing how much time it takes to add 10L or 20L and so on.

6. Take the total pressure head distribution by traversing the total head tube along the length of the test section. Record the total head reading on manometer h_8 with the tip of the probe adjacent to each tapping. The datum line is the side hole pressure tapping A associated with manometer h_1.

7. Increase the back pressure in the channel (thus reducing the volume flow rate) by throttling the outflow valve to give a maximum head difference of about 50 mm on the manometer.

8. Again, take the readings of the levels in manometers $h_1 - h_5$. Then repeat the procedure to record the total head at each tapping by traversing the total head tube along the test section.

9. Increase the back pressure one more time for the third flow rate reading by throttling the outflow valve to give the $h_1 - h_5$ difference approximately half way between that obtained in the above two settings.

10. As before, take manometer readings $h_1 - h_5$ and use the total head tube to traverse the test section for the total head readings at each tapping (tube h_8).

11. Switch off the pump and close the main valve.

Results/Questions:

1. Using your measured discharge rate, calculate the velocities at each of the tappings.

2. Calculate the total head, h_t, at each of the cross sections by adding your recorded static head and the calculated velocity head.

3. Plot the total head, h_t, as a function of distance, x, where x = 0 at tapping "A" and x = 14.54 cm at the outlet (tapping F).

4. What is the head loss between the inlet and the throat?

5. What is the head loss between the throat and the outlet?

6. Plot the calculated total head from above and also the measured total head (tube h_8) into a single graph. Do they differ? If so, why do you think this is the case? Discuss observed discrepancies.

7. Calculate the degree of pressure recovery. What does this indicate about the energy of the fluid as it passes through contractions and expansions?

Data:

Record your total head readings from tube h_8 in the last column.

Flow Rate 1:

Volume Collected V (m^3)	Time to Collect t (sec)	Flow Rate Q_v (m^3/sec)		Distance into Duct (m)	Area of Duct A (m^2)	Static Head h (m)	Velocity v (m/s)	Dynamic Head h_d (m)	Total Head h_t (m)
			h_1	0.00	490.9×10^{-6}				
			h_2	0.0603	151.7×10^{-6}				
			h_3	0.0687	109.4×10^{-6}				
Average flow rate			h_4	0.0732	89.9×10^{-6}				
			h_5	0.0811	78.5×10^{-6}				
			h_6	0.1415	490.9×10^{-6}				

Flow Rate 2:

Volume Collected V (m^3)	Time to Collect t (sec)	Flow Rate Q_v (m^3/sec)		Distance into Duct (m)	Area of Duct A (m^2)	Static Head h (m)	Velocity v (m/s)	Dynamic Head h_d (m)	Total Head h_t (m)
			h_1	0.00	490.9×10^{-6}				
			h_2	0.0603	151.7×10^{-6}				
			h_3	0.0687	109.4×10^{-6}				
Average flow rate			h_4	0.0732	89.9×10^{-6}				
			h_5	0.0811	78.5×10^{-6}				
			h_6	0.1415	490.9×10^{-6}				

Flow Rate 3:

Volume Collected V (m^3)	Time to Collect t (sec)	Flow Rate Q_v (m^3/sec)		Distance into Duct (m)	Area of Duct A (m^2)	Static Head h (m)	Velocity v (m/s)	Dynamic Head h_d (m)	Total Head h_t (m)
			h_1	0.00	490.9×10^{-6}				
			h_2	0.0603	151.7×10^{-6}				
			h_3	0.0687	109.4×10^{-6}				
Average flow rate			h_4	0.0732	89.9×10^{-6}				
			h_5	0.0811	78.5×10^{-6}				
			h_6	0.1415	490.9×10^{-6}				

Experiment 4

Pumps

Objectives:

- Learn how a single pump and pump combinations work by measuring flow rate (Q) and pump head (H) for different pump configurations.
- To develop an understanding of pump characteristic curves that address flow rate (Q) vs head (H), power (P), efficiency (E) based on experimentally collected data.
- Obtain an understanding for how Scaling works and to predict the H-Q characteristic for a pump at given speed from measured at different speeds.
- Investigate the effect of changing inlet head on pump performance, and address occurrences of Cavitation when the suction head increases.
- Construct a system curve based on your data [the Qs] and the provided pump characteristic curve to find the duty point.

Background:

Read chapter 5.6, [5.11]; look at example 5.4 (& fig. 5.13) & [5.5 & 5.6]; [] – optional

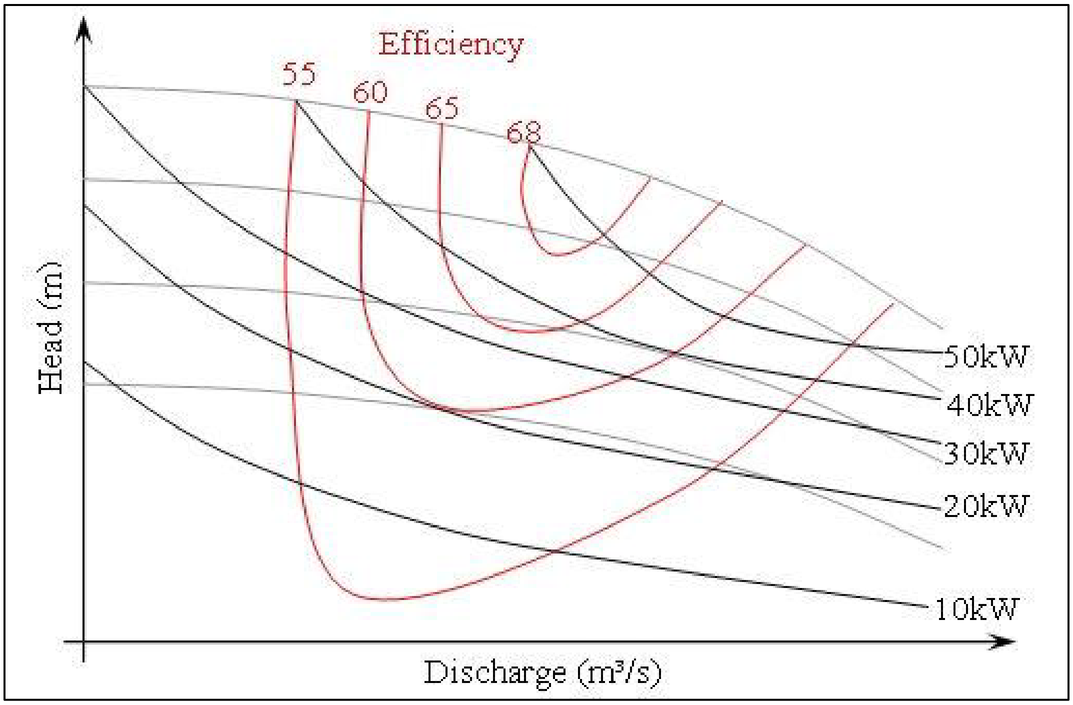


Figure 1 Sample of Pump Characteristic Curves

Pumps are used to transfer fluid in a system, either at the same elevation or to a new height. The obtained flow rate depends on the height to which the fluid is pumped. Each pump has a head-discharge relationship that is inversely proportional. The pump manufacturer provides this relationship, also known as the pump characteristic curve (figure 1).

In civil engineering applications, a single pump often cannot deliver the flow rate or head necessary for a particular system. However, two pumps (or more) can be combined in series to increase the height to which the fluid can be pumped at a given flow rate, or combined in parallel to increase the flow rate associated with a given value of head.

Set up Apparatus:

The apparatus can be set such that

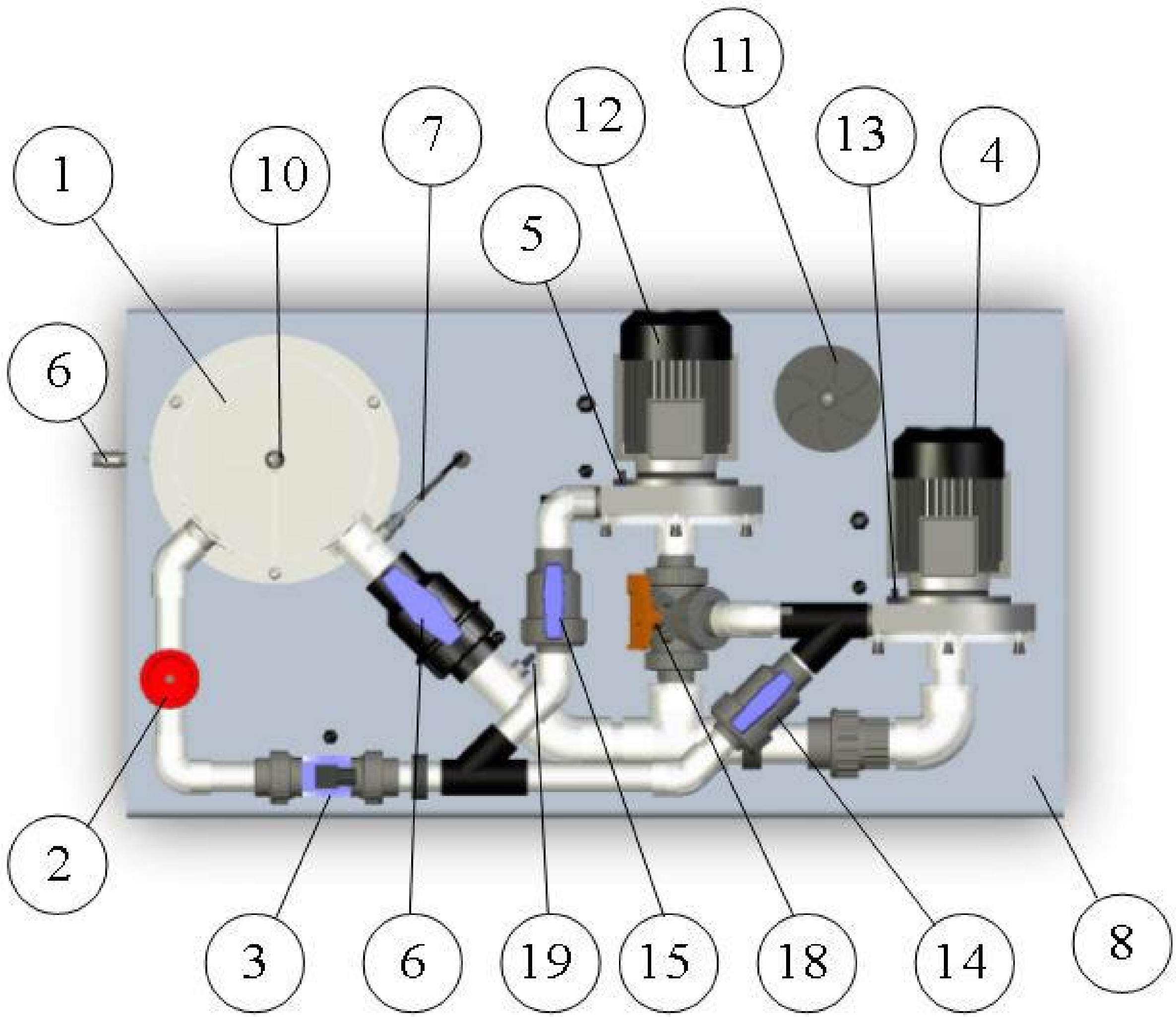
a) Only Pump 1 is operating. Its speed is controllable and thus can be used to develop a set of characteristic curves with various speed, inlet, and outlet settings.

b) Both pumps are operating, combined in either series or parallel. Note that pump 2 can only operate at its 80% (50Hz) or 100% (60HZ) setting, which is optimum setting. Make sure pump 1 also operates at the same setting.

Three additional notes:

1) The flow rate is controlled with gate valve that sits right in front of the return to the reservoir. Closing action will throttle down flow and create back pressure against which the pumps have to work. Also note that when the flow control valve is turned, the system is also changed – a partially closed valve has a higher loss coefficient, and the head loss is as usual proportional to $v^2/2g$
2) In most cases leave the outlet valve fully open. This valve is only used (slowly closing action) to increase the suction head for the pumps. This will eventually lead to cavitation. When the flow control valve is turned, the system is also changed – a partially closed valve has a higher loss coefficient, and the head loss is as usual proportional to $v^2/2g$.
3) In series connection, one pump is pushing, the other is drawing – both must be turned on and have nonzero regulator setting

Refer to the image below for the pump experiment and the details of the components.



Most important components:

2: is referred to as the Gate Valve; it controls the flow rate in the system

6: is referred to as the Inlet Valve; normally fully open it can be set to increase suction head

18: is referred to as the 3-way valve, it sets the flow path when testing for parallel and in series

4: is referred to as Pump1; it has a variable speed controller accessed via software

12: is referred to as Pump 2; its speed is set to 80% or 100% depending on power supply

14: is the Pump 1 outlet valve; if closed no flow leaves pump 1

15: is the Pump 2 outlet valve; if closed no flow leaves pump 2

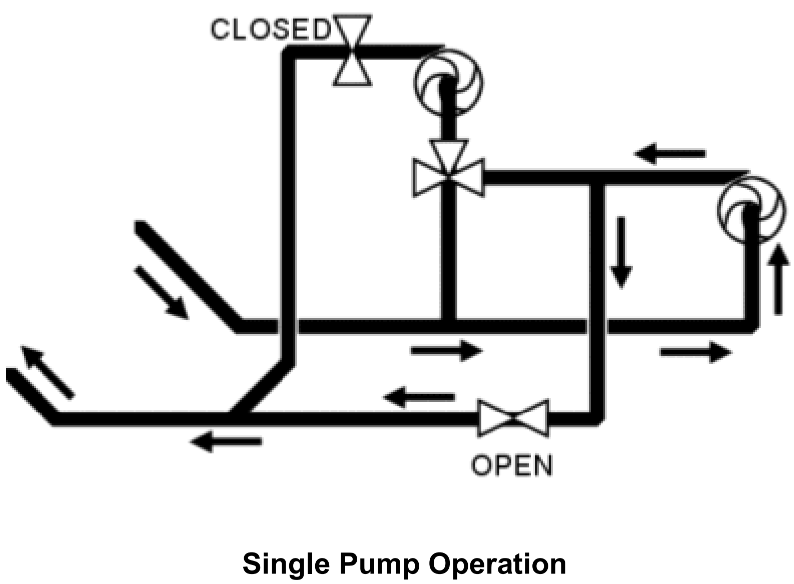
Experimental Tasks:

There is a set of 7 different experiments that can be carried out with this equipment. These are:

Exercise A – Intro to Pump Characteristics	together with Exercise D
Exercise B – Pump Characteristic Curves	together with Exercise C
Exercise C – Intro to Scaling	together with Exercise B
Exercise D – Effect of Inlet Head	together with Exercise A
Exercise E – Identification of Operating or Duty Point	Single
Exercise F – Pumps in Series	together with Exercise G
Exercise G – Pumps in Parallel	together with Exercise F

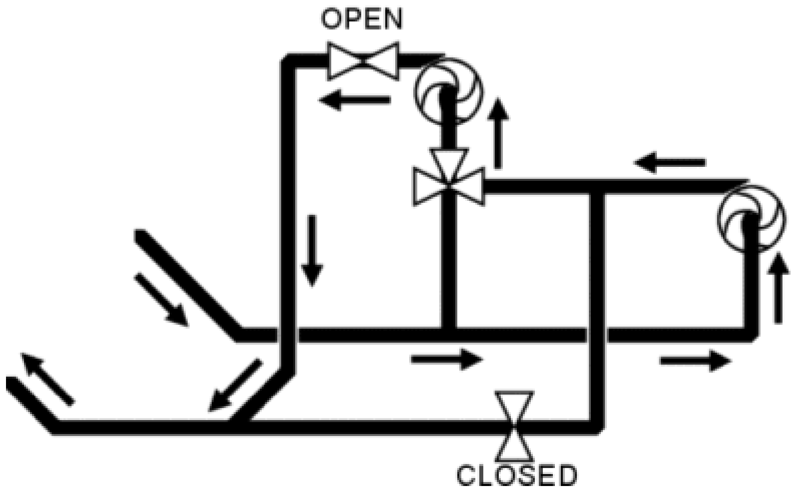
We cannot possibly carry out all of them but will identify two of them for a given lab date. For these specific assignments (2) in any given semester please refer to the course instructor and the website.

System Settings:



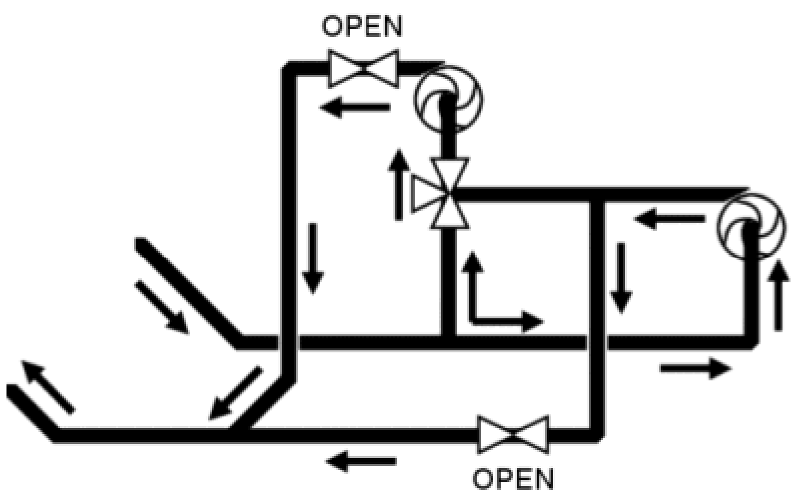
Single Pump Operation

Note the position of the 3-way valve. It can be in either parallel or series (as it shown above in the sketch) configuration. As long as the outlet valve for pump is closed there will be no flow through that pump.



Pumps in Series Operation

Note, the change of the valve settings. While the 3-way valve can remain unchanged from its Single-Pump operation, outlet valve for pump 1 is now closed, while outlet valve for pump is now open.



Pumps in Parallel Operation

Note, the change of the valve settings. The 3-way valve is set to allow throughflow while blocking flow from pump 1 to reach pump 2. On the other side, both pump outlet valves are now in the open position.

Exercise A – Intro to Pump Characteristics

Theory
The operating characteristics of a centrifugal pump may be described or illustrated by using graphs of pump performance. The three most commonly used graphical representations of pump performance are:

- Change in total head produced by the pump, Ht
- Power input to the pump, Pm
- Pump efficiency, E

Total Head
The change in total head produced as a result of the work done by pump can be calculated as:

H_t = Change in static head + change in velocity head + change in elevation

$= H_s + H_v + H_e$

where

$$H_s = \text{Change in static head} = \frac{(P_{out} - P_{in})}{\rho g}$$

where

P_{in} = fluid pressure at inlet in Pa

P_{out} = fluid pressure at outlet in Pa

(**Note:** Pressure and head are equivalent for water, as water is the benchmark against which other liquids are measured. Water has a Specific Gravity of 1. If a liquid other than water is used, head is obtained by dividing the pressure by the specific gravity)

$$H_v = \text{Change in velocity head} = \frac{(V_{out} - V_{in})^2}{2g}$$

where

V_{in} = fluid velocity at inlet in m/s

V_{out} = fluid velocity at outlet in m/s

H_e = Change in elevation = Vertical distance between inlet and outlet

= 0.075 m for Fm51

Power Input
The mechanical power input to the pump may be calculated as:

P_m = rotational force x angular distance

$= 2.\pi.n.t$

where

n = rotational speed of pump in revolutions per second

t = shaft torque in Nm

Pump efficiency

The efficiency of the pump may be calculated as:

$$E = 100 \times \frac{P_h}{P_m}$$

where

P_h = hydraulic power imparted to fluid

$= H_t.Q.\rho.g$

where

Q = volume flow rate in m³/s

P_m = mechanical power absorbed by pump

$= 2.\pi.n.t$

Each of these parameters is measured at constant pump speed, and is plotted against the volume flow rate, Q, through the pump. An example of this of graphical representation of pump performance is given in Figure 2, below.

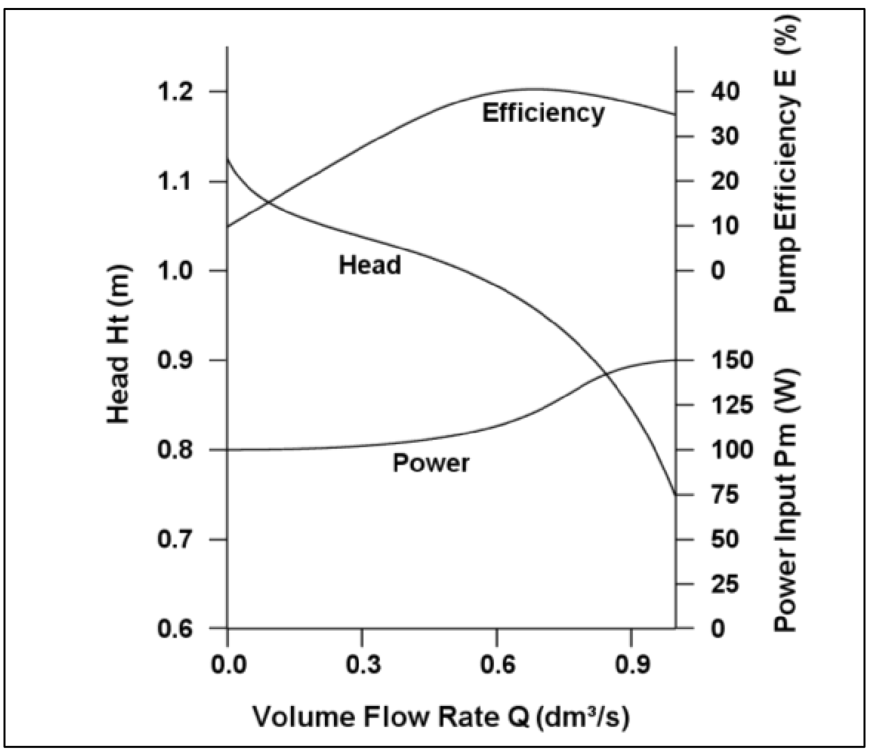


Figure 2 Examples for Pump Performance Curves

Examining Figure A1, the general performance of the pump can be determined.

The H_t-Q curve shows the relationship between head and flow rate. The change in head decreases as flow rate increases (head increases as flow rate decreases). This type of curve is referred to as a *rising characteristic curve*. A stable head-capacity characteristic curve is one in which there is only one possible flow rate for a given head, as in the example here.

The P_m-Q curve shows the relationship between the power input to the pump and the change in flow rate through the pump. Outside the optimum operating range of the pump this curve flattens, so that a large change in pump power produces only a small change in flow velocity.

The E-Q curve shows the pump capacity at which the pump operates most efficiently. In the example here, the optimum operating capacity is 0.7 dm^3/s, which would give a head of 1.2m. When selecting a pump for an application where the typical operating capacity is known, a pump should be selected so that its optimum efficiency is at or very near that capacity.

Equipment Set Up

Ensure the Drain Valve is fully closed and that the reservoir is filled to within 10 of the rim.

Ensure the inlet valve and the gate (flow control) valve are fully open.

Set the 3-way valve for flow in parallel, and close the Pump2 outlet valve**.** This will prevent flow through Pump2, thus directing all the flow through Pump1.

Make sure the data-interface is switched on, and that it is connected to a PC running the control software for the pump set up.

Procedure

- In the software, set Pump1 to 80%
- Allow water to circulate until all air has been flushed from the system
- Close the gate (flow control) valve to give a flow rate Q of 0 (note that the pump will not run well with the gate valve closed or nearly closed, as the back pressure produced is outside normal operating parameters. The pump should run more smoothly as the experiment progresses)
- Select the GO icon to record the sensor readings and pump settings on the results table of the software.

- Open the gate valve to permit a low flow rate. Allow sufficient time for the sensor readings to stabilize and then select the GO icon to record the next set of data.

- Open the gate valve in small increments, allowing the sensor readings to stabilize then recording the sensor and pump data each time.

- Using the arrow buttons on the software display, reduce the pump speed to 0%. Select “Save” or “Save As …” from the ‘File’ menu and save the results with a suitable file name (e.g. the data and the exercise).

- Turn off the data interface

- Make sure to copy/save the data from the laptop to a memory stick.

Results

1) Plot a graph of Head against Flow Rate.

2) Plot a graph of Mechanical Power against Flow Rate on one axis, and Efficiency against Flow Rate on the secondary axis

3) Examine and describe the shapes of the graphs obtained, relating this to the changing performance of the pump as the capacity (flow rate) changes. Determine the maximum efficiency and the flow rate at which it occurs, and mark the point of max efficiency on the performance curve.

4) Compare the shapes of the curves obtained to the example presented in Figure 2. Discuss any similarities and differences between the example presented and Pump1.

Exercise B – Pump Characteristics Curves

One way of illustrating pump characteristics is to construct contour lines of constant power or efficiency on a graph of pump head plotted against pump discharge. These allow engineers to see the max efficiency of a pump over a range of operating parameters, which can assist in the selection of an appropriate pump to suit particular conditions. An example is given below

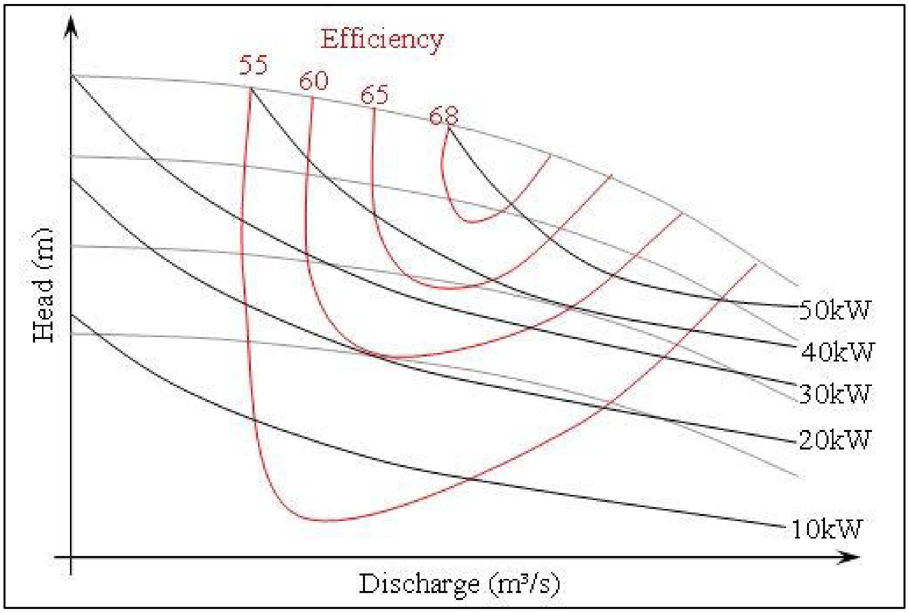


Figure 3 Family of Efficiency Curves overlain with other Characteristic Curves

Pump manufactures typically publish information on the performance of their pumps in the form of this type of chart. In addition to the use of these charts in in initially selecting a pump, the charts may also be used to compare actual pump performance with that expected. If the pump performance deviates significantly then the system must be investigated for problems and design flaws, and if the pump initially performs as expected but later displays a change in performance then the pump should be investigated for faults.

Equipment Set Up

Ensure the Drain Valve is fully closed and that the reservoir is filled to within 10 of the rim.

Ensure the inlet valve and the gate (flow control) valve are fully open.

Set the 3-way valve for flow in parallel, and close the Pump2 outlet valve**.** This will prevent flow through Pump2, thus directing all the flow through Pump1.

Make sure the data-interface is switched on, and that it is connected to a PC running the control software for the pump set up.

Procedure

- In the software, set Pump1 to 100% and allow water to circulate until all air has been flushed from the system

- Close the gate (flow control) valve to give a flow rate of Q of 0. (note that the pump will not run well with the gate valve closed or nearly closed, as the back pressure produced is outside normal operating parameters. The pump should run more smoothly as the experiment progresses)

- Select the GO icon to record the sensor readings and pump settings on the results table of the software.

- Open the gate valve to permit a low flow rate. Allow sufficient time for the sensor readings to stabilize and then select the GO icon to record the next set of data.

- Repeat by opening the gate valve in small increments, allowing the sensor readings to stabilize then recording the sensor and pump data each time.

- Create a new results sheet by selecting the ‘Next’ icon (you may also wish to save the results at this time to avoid losing the data in the event of problems)

- Close the gate valve and set Pump1 to 90%

- Select the GO icon to record the sensor readings and pump settings on the new results table.

- Open the gate valve to permit a low flow rate. Allow sufficient time for the sensor readings to stabilize and then select the GO icon to record the next set of data.

- Repeat by opening the gate valve in small increments, allowing the sensor readings to stabilize then recording the sensor and pump data each time.

- Repeat the procedure at 80%, 70%, and 60%, creating a new results sheet for each setting (and saving the results if desired – the same file may be overwritten each time as more data is added). We recommend to rename each sheet of results in the software with the corresponding pump setting.

- Ensure results are saved using ‘Save’ or “Save As …’ from the software File menu after taking the final set of results.

- Do not forget to copy or save these files to a thumb stick

Results

1) On the same graph plot total Head, H_T, against Flow Rate Q for each setting.

2) Select a value for efficiency, for example 30%,. On each line plotted, mark the points at which an efficiency of 30% is achieved. Where the pump performance at a particular setting does not ever correspond to the efficiency chosen, note whether the efficiency would lie above or below the line. Join the marked points to form a smooth curve.

3) Repeat for other efficiency values, for example 40% and 50%, to give a family of efficiency curves.

4) Create and/or print a second head-flow rate graph for all pump frequencies. Using the same procedure as for drawing contour lines fo constant efficiency, produce curves for constant mechanical power.

5) Examine and describe the shapes of the efficiency and power graphs obtained. Are the shapes consistent? How do they relate to the head-flow rate characteristic? How do the efficiency and power curves relate to each other?

6) Compare the results to the example pump curves presented in the theory section. How does the pump in the example compare to Pump1 on the experimental set up in terms of capacity, power, and efficiency?

Exercise C – Intro to Scaling

Theory

When selecting a pump for a system, it is seldom practical to test the performance of every size of pump in a manufacturer's range at all speeds at which it may be designed to run. It is therefore useful to have a mathematical solution that allows assumptions can be made about operating characteristics of a pump running at one speed, impeller size, etc. from experimental results taken at another.

The multiple curves obtained from plotting measured pump characteristics on dimensional axes can be reduced to a single curve if appropriate dimensionless groups are used. Provided the effects of fluid viscosity on pump performance are small, and that cavitation is not occurring, the characteristic of a given type and shape of pump may be represented by:

$$\frac{gHt}{n^2D^2} = \int \frac{[Q]}{nD^3}$$

where

n is the pump speed (rpm), and

D is the impeller diameter (m)

For a single curve of the type suggested by this equation to represent more than one operating condition of the particular type of pump, the criterion of *dynamic similarity* must be fulfilled. That is, all fluid velocities at corresponding points within the machine are in the same direction and proportional to impeller speed. When this is the case, as for a particular pump operated at different speeds, a simple graph of data is formed, as depicted in Figure **4**.

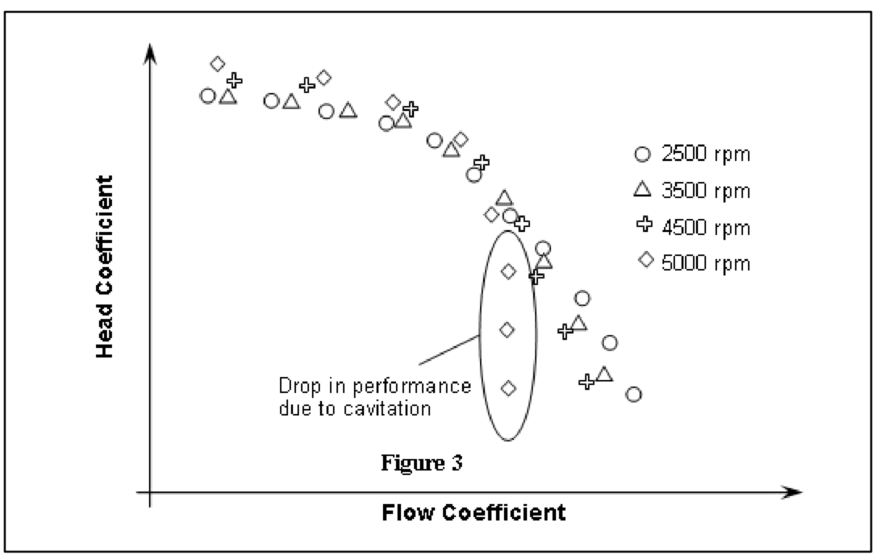


Figure 4 Dim-Less head - flow rate characteristics of a particular centrifugal pump operated at different speeds

The dimensionless equation given previously is the basis from which the *affinity laws* are derived. The affinity laws allow the performance of *geometrically similar* pumps of different sizes or speeds to be predicted accurately enough for practical purposes.

The methods used for deriving the affinity laws will not be presented here, but the laws are as follows:

Power coefficient $$\boxed{\bar{P} = \frac{P}{\rho n^3 D^3}}$$

Flow coefficient $$\phi = \frac{Q}{nD^3}$$

Head coefficient $$\psi = \frac{gHt}{n^2 D^2}$$

These laws are most often used to calculate changes in flow rate, head and power of a pump when the size, rotational speed or fluid density is changed. The following formulae are derived from the above considerations, and allow calculation of head Ht, power Pm and efficiency E at one speed n_1 to be deduced from those measured at another speed n_2:

$$\frac{Q_1}{Q_2} = \frac{n_1}{n_2} \qquad \frac{H_{t1}}{H_{t2}} = \frac{n_1^2}{n_2^2} \qquad \frac{P_{m1}}{P_{m2}} = \frac{n_1^2}{n_2^2}$$

More generally, the relationship between two geometrically similar machines with characteristic diameters D_1 and D_2 operating at rotational speeds n_1 and n_2 is shown in Figure C2. For any two points at which values of (gH / n^2D^2) and (Q / nD^3) are the same, it follows that:

$$H_2 = H_1 \left(\frac{n_2}{n_1}\right)^2 \left(\frac{D_2}{D_1}\right)^2$$

and

$$Q_2 = Q_1 \frac{n_2}{n_1} \left(\frac{D_2}{D_1}\right)^3$$

These are termed *corresponding points*.

The power coefficient $\dfrac{P_m}{\rho n^3 D^5}$ and the efficiency E can be compared in a similar manner.

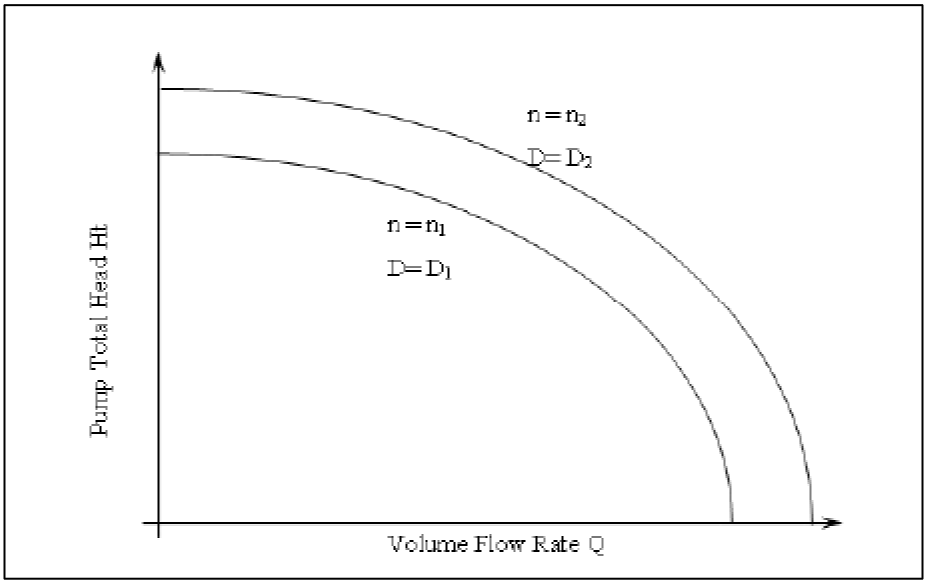


Figure 5 Relationship of performance characteristics for geometrically similar machines operating at different speeds

Equipment Set Up

Ensure the Drain Valve is fully closed and that the reservoir is filled to within 10 of the rim.

Ensure the inlet valve and the gate (flow control) valve are fully open.

Set the 3-way valve for flow in parallel, and close the Pump2 outlet valve**.** This will prevent flow through Pump2, thus directing all the flow through Pump1.

Make sure the data-interface is switched on, and that it is connected to a PC running the control software for the pump set up.

Procedure

- **NOTE!** The results from exercise B may be used to perform the calculations and to create the graphs for this exercise. If no results are available proceed as follows.

- In the software, set Pump1 to 80% and allow water to circulate until all air has been flushed from the system

- Close the gate (flow control) valve to give a flow rate of Q of 0. (note that the pump will not run well with the gate valve closed or nearly closed, as the back pressure produced is outside normal operating parameters. The pump should run more smoothly as the experiment progresses)

- Select the GO icon to record the sensor readings and pump settings on the results table of the software.

- Open the gate valve to permit a low flow rate. Allow sufficient time for the sensor readings to stabilize and then select the GO icon to record the next set of data.

- Repeat by opening the gate valve in small increments, allowing the sensor readings to stabilize then recording the sensor and pump data each time.

- Create a new results sheet by selecting the 'Next' icon (you may also wish to save the results at this time to avoid losing the data in the event of problems)

- Close the gate valve and set Pump1 to 60%

- Select the GO icon to record the sensor readings and pump settings on the new results table.

- Open the gate valve to permit a low flow rate. Allow sufficient time for the sensor readings to stabilize and then select the GO icon to record the next set of data.

- Repeat by opening the gate valve in small increments, allowing the sensor readings to stabilize then recording the sensor and pump data each time.

- Ensure results are saved using 'Save' or "Save As …' from the software File menu after taking the final set of results.

- Do not forget to copy or save these files to a thumb stick

Results

The results taken at 80% will be used with the affinity laws to give predicted results at 60%. This will then be compared to the actual results at 60%.

1) Plot a graph of total Head, H_T, against Flow Rate Q at 80% pump setting

2) The software uses the affinity laws

$$\frac{Q_1}{Q_2} = \frac{n_1}{n_2} \quad \text{and} \quad \frac{H_{t1}}{H_{t2}} = \frac{n_1^2}{n_2^2}$$

to calculate the predicted values of H_{t2} at flow rates Q_2 and a setting of 60% form the measured values of H_{t1} and Q_1 and the values n_1 = 70 and n_2 = 50

3) Plot a graph of Predicted Head against Predicted Flow Rate.

4) Plot a graph of the measured Total Head against Flow Rate at 60%

5) Compare the predicted results at 60% with the measured results. How accurate were the values obtained using the affinity laws? Discuss the advantages and disadvantages of this technique for pump system design.

Exercise D – Effect of Inlet Head

Theory

In both the design and operation of a rotodynamic machine, careful attention has to be paid to the fluid conditions on the suction side. In particular, it is important to check the minimum pressure that can arise at any point to ensure that cavitation does not take place.

Cavitation

If the pressure at any point is less than the vapour pressure of the liquid at the temperature at that point, vaporisation will occur. This is most likely to arise in the suction side where the lowest pressures are experienced. The vaporised liquid appears as bubbles within the liquid, and these subsequently collapse with such force that mechanical damage may be sustained. This condition, known as *cavitation*, is accompanied by a marked increase in noise and vibration in addition to the loss of head.

In addition to the potential for physical damage to the pump from cavitation, both from the resulting vibration and from the explosive force of the collapsing bubbles of vapour, pumps cannot pump vapour effectively. Hence if cavitation occurs then the pump may not be capable of developing the suction head necessary to reach the required operating point.

Net Positive Suction Head Required

Manufacturers commonly specify a Net Positive Suction Head (*NPSH*), based on pump test results. The usual testing to determine the NPSH will involve running the pump with water at different capacities, while throttling (reducing the flow in) the inlet (suction) side. The suction pressures at which the first sign of vaporisation appear are noted for each capacity. These are then converted into head values and are published on the pump characteristic curve as the Net Positive Suction Head Required (NPSHr) or just NPSH. NPSH is the amount by which the pressure at this point must exceed the vapour pressure of the liquid.

Net Positive Suction Head Available

The Net Positive Suction Head Available (NPSHa) depends on the system in which the pump is used, and is calculated according to system conditions. The basic calculation for an existing system using water as the working fluid may be approximated as:

$$NPSHa = H_{atmos} - H_{vapour} + H_{in} + H_v$$

Where

H_{atmos} = Barometric (ambient) pressure, expressed as a head of water in mm.

H_{vapour} = Vapour pressure of water at maximum expected temperature, expressed as an equivalent head of water in mm.

H_{in} = Gauge (sensor) pressure at inlet (note that value is relative to atmosphere, and thus in some circumstances may be negative), expressed as a head of water in mm.

H_v = Velocity head $= \dfrac{V_{in}^2}{2g}$

NPSH here is calculated in mm of water. In some pump datasheets it may be expressed in inches of water. It may also be calculated as a pressure by summing the component pressures. To convert velocity head to equivalent pressure, use

$$P_v \quad = \text{Pressure due to velocity head} \quad = \frac{V_{in}^{\ 2}}{2g} \times \rho \times g$$

Equipment Set Up

Ensure the Drain Valve is fully closed and that the reservoir is filled to within 10 of the rim.

Ensure the inlet valve and the gate (flow control) valve are fully open.

Set the 3-way valve for flow in parallel, and close the Pump2 outlet valve**.** This will prevent flow through Pump2, thus directing all the flow through Pump1.

Make sure the data-interface is switched on, and that it is connected to a PC running the control software for the pump set up.

Procedure

- In the software set Pump1 to 30%, and fully open the gate (flow control) value to permit water to circulate and flush out remaining air pockets.

- Close the inlet valve just a little but enough to impose a noticeable flow reduction

- Select the “GO” icon to record the sensor readings and pump settings on the results table of the software.

- Close the inlet valve a little more. Allow for sufficient time for the sensor readings to stabilize then select the “GO” icon to record the next set of data.

- Repeat, making small step changes in the setting of the inlet valve, allowing the sensor readings to stabilize then recording the sensor and pump data each time.

- As soon as the inlet valve is fully closed, take one final set of results using the GO icon then fully open the valve again.

- Create a new results table using the TABLE icon.

- Set the pump to 60% then repeat the procedure at this new pump setting.

- Repeat for a pump setting of 90% and remember to create a new results sheet.

- Bubbles will be noted around the impeller during the experiment, as air comes out of solution as a result of decreased fluid pressure. It is, however, very unlikely that true cavitation will occur within the normal operating conditions of the system. If it should occur, cavitation can be readily recognized by a drop or fluctuation in the head developed by the pump, and by the distinctive noise (variously described as sounding like crackling cellophane and sound as if the pump were full of rocks or marbles). If cavitation should begin to develop, use the ‘Note’ facility to describe the observations made then take a set of data to add that note to the sensor readings. As soon as a set of readings has been taken, increase the suction head until cavitation ceases to avoid causing damage to the impeller.

- If cavitation does occur, it is due to a combination of factors which may include high fluid temperature, high fluid flow rate (high impeller speed), low ambient pressure and low inlet head.

- Select ‘Save’ or ‘Save As …’ from the ‘File’ menu and save the results with a suitable file name (e.g. date, group number, and experiment number).

Results

1) On a single graph, plot the pump capacity (flow rate) against the suction head for each set of data.

2) One a single graph, plot the Net Positive Suction Head Available against pump capacity.

3) In the unlikely event that cavitation was observed, print out the second graph and mark on it any point at which cavitation appeared.

4) Describe the effect of changing suction head on pump performance.

5) Discuss the use of NPSH charts in the design of a system and he choice of a suitable pump.

6) If cavitation was observed, describe the conditions under which it appeared.

Exercise E – System Characteristics: Duty or Operating Point

Method

By varying the outlet flow control valve at fixed pump speed (to obtain the pump head - flow characteristic) and varying the pump speed at fixed valve setting (to obtain the system head - flow characteristic) then comparing the curves to obtain the duty point.

Theory

System analysis for a pumping installation is conducted to select the most suitable pump for a particular application by defining the operating point. System analysis involves calculating head - flow curves for the system (frictional losses in valves, pipes, fittings etc.) and the use of these curves with those of available pumps. The system curve is a graphic representation of all possible duty points in so far that the total dynamic head (static lift plus kinetic energy losses) is plotted against discharge flows from zero to the expected maximum, and a typical set are shown in Figure E1 for different systems with the same static head but different frictional losses.

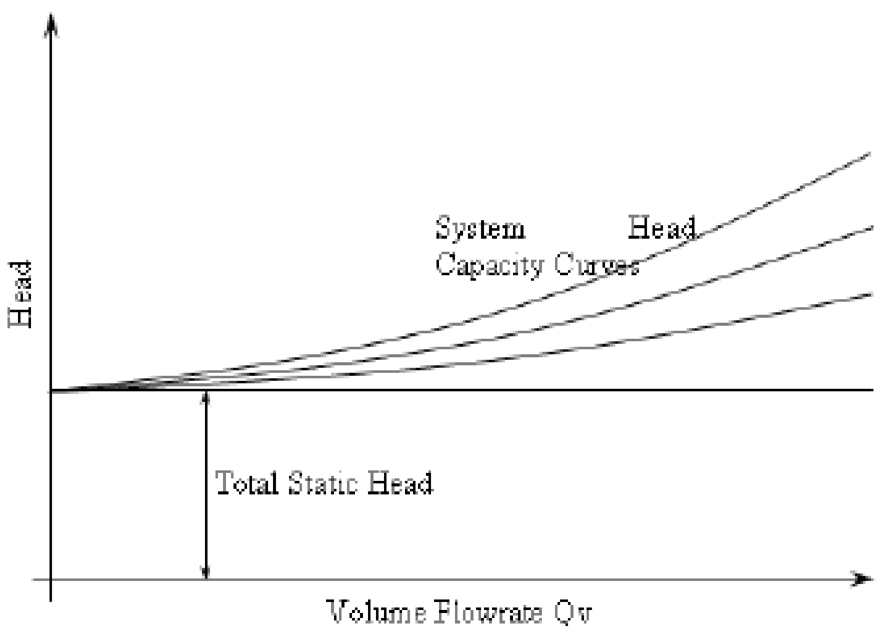


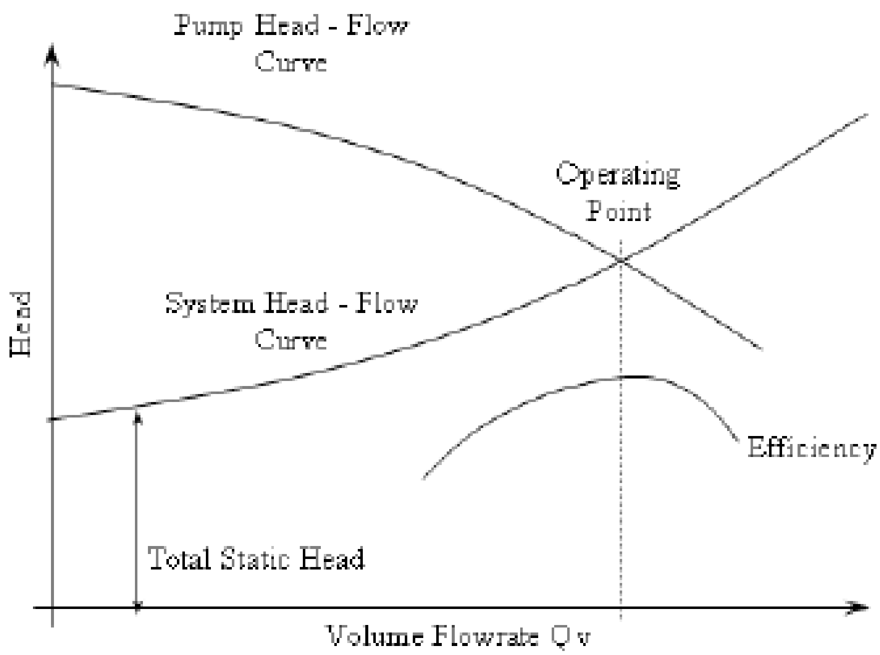
Figure E1: Typical head - flow curves for a pumping installation (pipes, valves etc.)

As demonstrated in previous exercises, pump characteristic curves illustrate the relationship between head, flow, power and efficiency over a wide range of possible operating conditions, but they do not indicate at which point on the curves the pump will operate. The operating point (or duty point) is found by plotting the pump head - flow curve with the system head - flow curve, as shown in figure E2. The intersection of the two curves represents the head and flow that the pump will produce if operated in the given piping system. The position of the operating point will vary if the pump is changed for a similar model with different characteristics or if the system is changed to include different pipe fitting, pipe lengths etc. For efficient operation the operating point and the maximum pump efficiency should occur at the same flowrate.

By varying the outlet flow control valve at fixed pump speed (to obtain the pump head - flow characteristic) and varying the pump speed at fixed valve setting (to obtain the system head - flow characteristic) then comparing the curves to obtain the duty point.

The head - flow curve for the pump is obtained by monitoring the pressure at the outlet of pump 1 while varying the outlet flow control valve operating (speed of the pump fixed).

The head - flow curve for the system is obtained by monitoring the pressure at the outlet of pump 1 while varying the operating speed of the pump (outlet flow control valve fixed at some intermediate setting).



Equipment Set Up

NOTE: Pump2 is not used in this exercise.

Ensure the Drain Valve is fully closed and that the reservoir is filled to within 10 of the rim.

Ensure the inlet valve and the gate (flow control) valve are fully open.

Ensure that Pump2 is switched off in the software then set the 3-way valve for flow in parallel, and close the Pump2 outlet valve**.** This will prevent flow through Pump2, thus directing all the flow through Pump1.

Make sure the data-interface is switched on, and that it is connected to a PC running the control software for the pump set up.

Switch on Pump1 in the software and set Pump1 speed to 100% then allow the system to fully prime and flush out remaining air bubbles.

The exercise will be conducted in two parts; Part1 measures the pump head-flow characteristics, Part2 measures the system head flow characteristic allowing the two characteristics to be compared in the same graph.

Procedure – Part1 (Pump Characteristics)

- In the software set Pump1 to 100%, and fully open the gate (flow control). Make sure the readings are stable.

- Select the GO icon to record the sensor readings and pump settings on the results table of the software.

- Observe the maximum flow rate reading obtained then divide this by 10 to give suitable increments when adjusting the flow control valve.

- Gradually close the flow control valve to achieve 90% of the max flow, allow the readings to stabilize and then select the GO icon again for another result recording.

- Repeat while reducing the flow rate in 10% steps, recording a data sample at each step, with a final set of data taken at 0% flow rate (flow control valve fully closed)

Procedure – Part2 (System Characteristics)

- Flow through the pump will be changed by varying the speed setting using the Laptop software rather than by varying the outlet flow control valve as in the previous set of measurements.

- Select the ‘Table’ icon to create a new results sheet.

- Select a position for the outlet flow control valve such that it is partly closed and forming a significant resistance to flow, e.g. approximately 40% of the maximum available flow rate. This setting will be maintained throughout this part of the exercise.

- Allow the readings to stabilize then select the GO icon to record the sensor readings and pump settings on the results table of the software.

- Set the pump to 90%, and allow the readings to stabilize then record another set of data using the GO icon again.

- Repeat while reducing the pump speed setting in 10% increments, recording a data sample at each step with a final set of data taken at 0% pump speed. The measurements will produce the 'system' head curve, as described in the Theory section.

- NOTE: Readings can be taken at low settings of pump speed but prolonged operation at low speeds should be avoided to prevent overheating of the motor. After taking readings at low speeds return the pump speed to 100%.

- Select the 'TABLE' icon to create a new results sheet.

- Ensure pump speed is back to 100%

- Readjust the position of the control (flow rate) valve to give approximately 70% of max available flows rate.

- Let readings stabilize and record a new set of data using the GO icon.

- Set the pump to 90% and again record the data set.

- Repeat this while reducing the pump speed in 10% increments., recording a data sample at each step, with a final set of data taken at 0% pump speed. These measurements will produce another, different, 'system' head-flow rate curve.

- Select 'Save' or 'Save As …', form the file menu and save the results with a suitable file name (e.g. your group name and the exercise number).

Results

1) Plot a graph for flow rate (x-axis) against:
   y-axis 1:
   Run 1, Pump1 Total Head (The pump head-flow characteristic)
   Run 2, Pump1 Total Head (The system characteristic at one valve setting)
   Run 3, Pump1 Total Head (The system characteristic with a different valve setting)

   y-axis 2 (different scale):
   Run 1, Pump1 Efficiency (The pump efficiency-flow characteristic)

2) Observe the points on the graph at which the pump head curve intersects the two system head curves to obtain the duty (operating) points of the pump with two different system requirements.

3) Observe the flow rate at which these duty points occur compared with the corresponding flow rate for maximum pump efficiency and comment on the optimum system resistance curve to suite the pump.

4) If you can, repeat the above exercise to obtain a system resistance curve where the duty point of the pump coincides with the maximum pump efficiency.

5) Compare the graph obtained with the example given the Theory section.

Closing Remarks

The duty point of a centrifugal pump occurs where the pump head-flow curve intersects the system head-flow curve.

For maximum pump efficiency, essential when operating a large pump that requires a significant power input, the duty point should be close to the point of maximum efficiency.

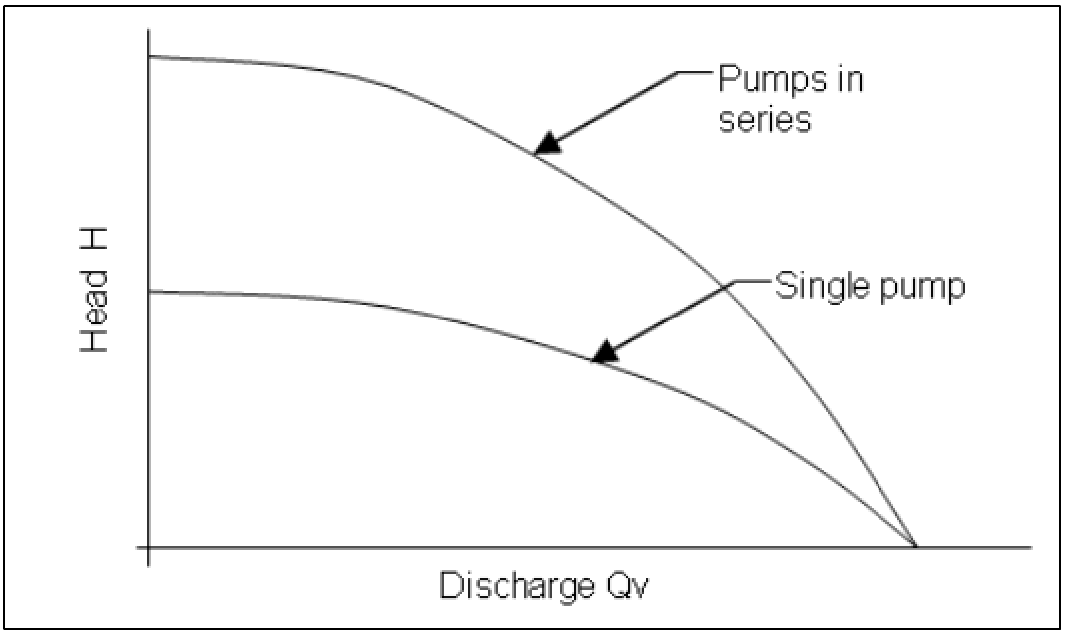
Where a pump produces too much flow for a particular system, a restrictor or valve can be used to reduce the flow but this is inefficient and wastes energy.

In a practical application the system resistance curve is calculated by adding the head loss due to the pipe friction and the head loss due to the fittings (minor losses) at different flow rates. This curve is then compared with the manufacturer’s head-flow curve for different pumps to determine the optimum combination.

Exercise F – Pumps in Series

Theory

A single pump may be insufficient to produce the performance required. Combining two pumps increases the pumping capacity of the system. Two pumps may be connected in series, so that water passes first through one pump and then through the second. When two pumps operate in series, the flowrate is the same as for a single pump but the total head is increased., The combined pump head-flowrate curve is found by adding the heads of the single pump curves at the same flowrate.



Equipment Set Up

Ensure the Drain Valve is fully closed and that the reservoir is filled to within 10 of the rim.

Make sure both pumps have the same impellers installed.

Ensure the inlet valve and the gate (flow control) valve are fully open.

Set the 3-way valve for flow in series, this is different from the previous set ups that mostly used flow in parallel set ups.

Ensure that the data interface unit is on and that you can see in the software that the ‘IFD: OK’ is displayed in the bottom right corner.

Procedure

- Both pumps must be used at the same setting in this experiment, to ensure identical performance. As the speed of Pump2 is fixed at its design operational point, Pump1 should be set to match – select 80% for a 50MHz electrical supply or 100% for 60MHz.

- Allow water to circulate until all air bubbles have been flushed from the system

- **Part 1: Single Pump Performance**

- Close Pump2 outlet valve and open Pump1 outlet valve

- In software interface set 'Mode' to 'Single' by selecting the appropriate radio button

- Rename results sheet to "Single'

- Use the GO icon to record your first set of data

- Close the gate (flow control) valve to reduce the flow by a small amount and use the GO icon to record your 2nd set of data in the table.

- Continue to close the gate valve to give incremental changes in flowrate, recording the data each time.

- After taking the final set of data, fully open the gate valve.

- **Part 2: Series Pump Performance**

- Create a new results sheet using the "Table' icon. Rename this sheet to "Series'

- In the software, on the mimic diagram, set the 'Mode' to 'Series' by selecting the appropriate radio button

- Open Pump2 outlet valve, close Pump1 outlet valve and wat for any air to circulate out of the system

- Select the GO icon to record the sensor readings and pump settings on the results table of the software

- Close the gate (flowrate) valve to reduce the flow by a small amount. Use the GO icon again to record the data in the table

- Continue to close the gate valve to give incremental changes in flowrate, recording the sensor data each time

- After taking the final set of data, fully open the gate valve again

- **NOTE!** You may proceed straight to exercise G (Pumps in Parallel) now without closing the software; otherwise save the results and make sure they are available for exercise G when required. You may want to save the results anyways before proceeding just to be on the safe side. You can always overwrite this result sheet with the combined results at the end of exercise G, in case it went through without a hitch.

Results

1) Showing flowrate on the x-axis plot a graph of total head gain for the single pump and for two pumps connected in series. Calculate the difference between the total head gain for single and series pumps

2) Does the total head gain for the two pumps in series match the theoretical prediction of twice the head gain for a single pump (assuming the two pumps used gave identical performance?)

3) Give example of application where pumps might be connected in series.

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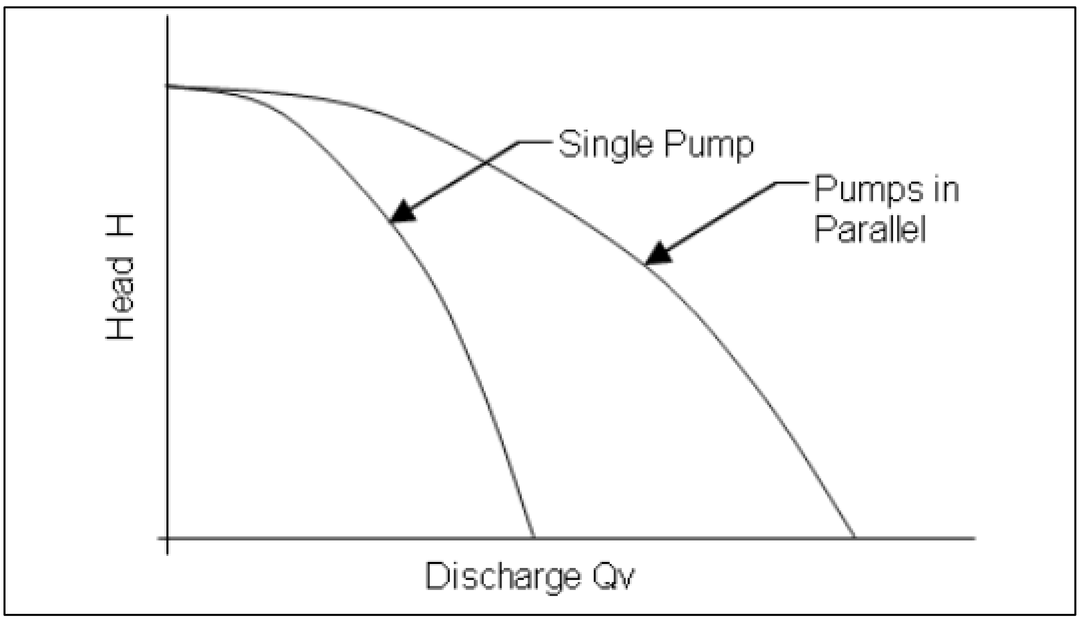
Exercise G – Pumps in Parallel

Theory

A single pump may be insufficient to produce the performance required. Combining two pumps increases the pumping capacity of the system. Two pumps may be connected in parallel, so that half the flow passes through one of the pumps and the other half through the second pump. When two pumps operate in parallel the total head increase remains unchanged but the flow rate is increased. The head-flowrate curve is found by adding the flowrates of the single pump curves at the same head.



Equipment Set Up

Ensure the Drain Valve is fully closed and that the reservoir is filled to within 10 of the rim.

Make sure both pumps have the same impellers installed.

Ensure the inlet valve and the gate (flow control) valve are fully open.

Set the 3-way valve for flow in parallel

Fully open both Pump1 and Pump2 outlet valves; this ensures that the outlet pressure on both pumps is the same.

Ensure that the data interface unit is on and that you can see in the software that the 'IFD: OK' is displayed in the bottom right corner.

Make sure to set the 'Mode' to "Parallel on the mimic diagram in the software GUI

Procedure

- Both pumps must be used at the same setting in this experiment, to ensure identical performance. As the speed of Pump2 is fixed at its design operational point, Pump1 should be set to match – select 80% for a 50MHz electrical supply or 100% for 60MHz.

- Allow air to circulate out from the system

- **NOTE!** If the software is still open from the previous exercise (F), create a new results sheet selecting the 'Table' icon and name it 'Parallel'. If it is NOT, load the results from the 'Single' experiment carried out from experiment 'F'.

- Select the GO icon to record your first data set

- Continue to close the gate (flowrate) valve to give incremental changes in flowrate, recording the sensor data each time

- After taking the final set of data, fully open the gate valve. Set Pump1 to 0% and switch off both pumps

Results

1) Showing flowrate on the x-axis plot a graph of total flowrate gain for the single pump and for two pumps connected in parallel. Calculate the difference between the flowrate gain for single and parallel pumps

2) Does the flowrate gain for the two pumps in parallel match the theoretical prediction of twice the flowrate gain for a single pump (assuming the two pumps used gave identical performance?)

3) Give example of application where pumps might be connected in parallel.

4) Compare the graphs for pumps in series and pumps in parallel, and describe the similarities and differences.

Experiment 5

Calibration of Sharp-Crested Weirs

Objectives:

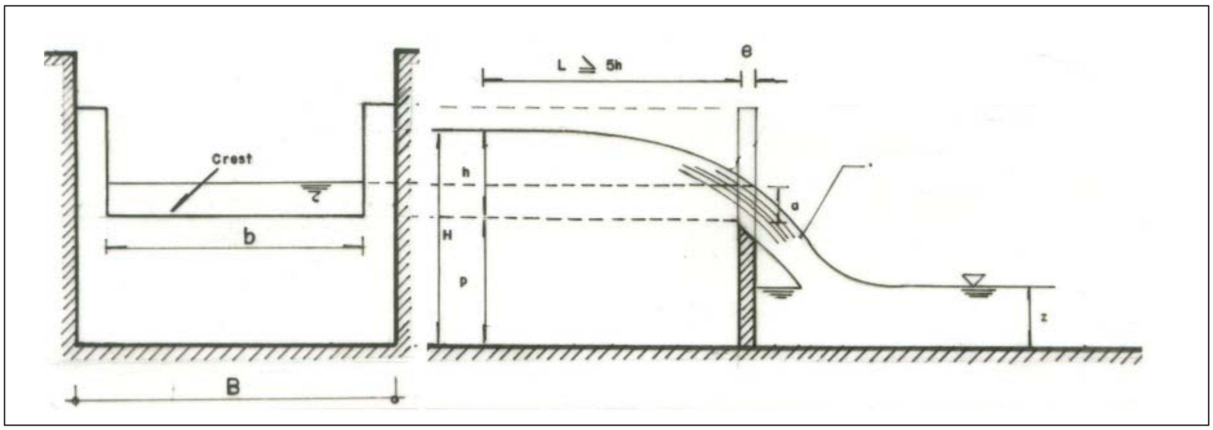
- Verify the discharge equation and estimate discharge coefficients for a rectangular and a V-notch weir.
- Measure flow data that is depend on the flow rate and shape of the weir, and use these data points to modify he equation that results from the theoretical relationships between these variables

Background:

A weir is an overflow structure extending across a stream of a channel and normal to the direction of the flow. They are normally categorized by their shape as either sharp-crested or broad-crested. This laboratory experiment focuses on sharp-crested weirs only. Two different types of weirs will be introduced: The rectangular weir and the V-notch weir.

Theory:

1. **Rectangular Weir**



Consider the flow through a rectangular notch or sharp-crested weir as shown in Figure 8-1. A horizontal differential element is taken at a depth y below the free surface. The area of the element is given by,

$$dA = B\,dy \qquad (5\text{-}1)$$

The velocity through the element is given by,

$$v = \sqrt{2gy} \tag{5-2}$$

Therefore, the theoretical discharge through the element is,

$$dQ = B\sqrt{2gy}dy \tag{5-3}$$

Integrating Eq. 8-3 yields the theoretical discharge,

$$Q_t = B\sqrt{2g}\int_0^H y^{1/2}dy \tag{5-4}$$

or,

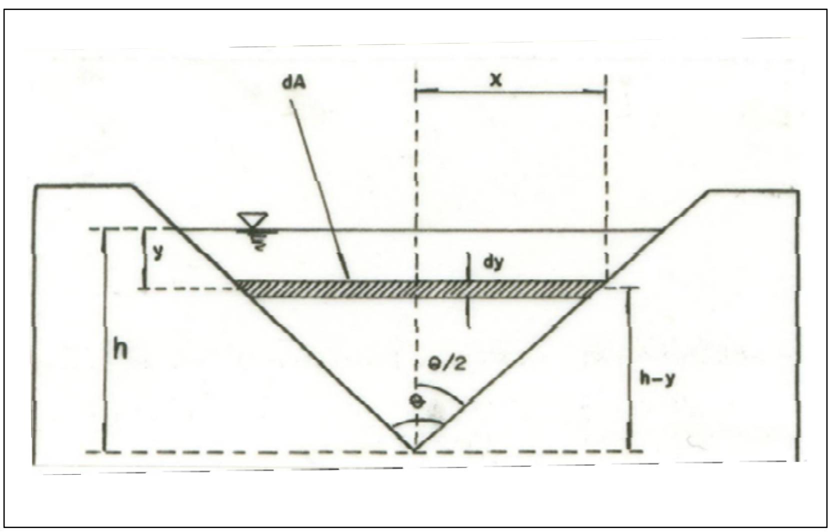
$$Q_t = \frac{2}{3}B\sqrt{2g}H^{3/2} \tag{5-5}$$

The actual discharge is given by,

$$Q_a = C_d\frac{2}{3}B\sqrt{2g}H^{3/2} \tag{5-6}$$

where C_d = the coefficient of discharge, $K = \frac{2}{3}B\sqrt{2g}$, $N = \frac{3}{2}$ and B = 3 cm.

2. V-Notch Weir



Consider the flow through the triangular notched weir shown in above Figure. Consider an element at depth y. The breadth of the element is given by,

$$B = 2\,(H - y)\tan\theta \tag{5-7}$$

and the area of the differential element is then given by,

$$dA = 2\ (H - y)\ tan\ \theta\, dy \tag{5-8}$$

while the velocity through the element is given by,

$$v = \sqrt{2gy} \tag{5-9}$$

The discharge through the element is,

$$dQ = 2(H - y)\sqrt{2gy}\,\tan\theta dy \tag{5-10}$$

and the total theoretical discharge is obtained by integrating Eq. 8-10,

$$Q_t = 2\tan\theta\sqrt{2g}\int_0^H (Hy^{1/2} - y^{3/2})dy \tag{5-11}$$

which yields,

$$Q_t = \frac{8}{15}\tan\theta\sqrt{2g}H^{5/2} \tag{5-12}$$

The actual discharge is given by,

$$Q_a = C_d\,\frac{8}{15}\tan\theta\sqrt{2g}H^{5/2} \tag{5-13}$$

in which C_d = the *coefficient of discharge*.

θ = 1/2 of the machined angle = 45°

N = 5/2 (triangle), and

$$K = \frac{8}{15}\sqrt{2g}\,\tan\theta$$

Experimental Procedure

- Measure the width of the weir.
- Turn on the pump and open the control valve until water discharges over the weir plate.
- Close the control valve and turn off the pump and allow water level to drop until water flow over the weir stops.
- Set Vernier height gauge to datum reading (water surface in the channel).
- Position the gauge at about halfway between the plate and the stilling baffle.

- Turn on the pump, open the control valve and adjust it to obtain the head H.
- After the conditions are stable, for each flow rate measure and record H.
- Take readings of volume discharged and time of discharge using the volumetric tank.
- Repeat five times for each weir type.

Data Analysis

Rectangular Weir

In a rectangular weir:

$$Q = \frac{2}{3} * C_d * b * \sqrt{2g} * h^{3/2}$$

Determine discharge coefficient as follows (take measurements for at least 4 different discharges (Q) and 2 to 3 trials to determine each value of Q):

1. Tabulate discharge, head and discharge coefficient.
2. By plotting a graph of the logarithm of the flow rate vs. the logarithm of the depth, compare the theoretical power law and coefficient with those obtained from the graph. Comment on your results.
3. Plot C_d vs Q for each measured Q.
4. Fit a function of the form $Y=cX^{3/2}$ for the data in 2. And from this c and what you know about the weir formula above determine C_d.

Answer in your report: Is C_d constant for this weir?

V-notch Weir

In a V-notch weir:

$$Q = \frac{8}{15} * C_d * \tan\left(\frac{\theta}{2}\right) * \sqrt{2g} * h^{5/2}$$

Determine discharge coefficient as follows (take measurements for at least 4 different discharges (Q) and 2 to 3 trials to determine each value of Q):

1. Tabulate discharge, head and discharge coefficient.
2. By plotting a graph of the logarithm of the flow rate vs. the logarithm of the depth, compare the theoretical power law and coefficient with those obtained from the graph. Comment on your results.
3. Plot C_d vs Q for each measured Q.
4. Fit a function of the form $Y=cX^{5/2}$ for the data in 2. And from this c and what you know about the weir formula above determine C_d.

Answer in your report: Is C_d constant for this weir?

Data Table:

Rect. Weir		Vol (L)	t (s)	V. weir		Vol (L)	t (s)
Q1	trial 1			Q1	trial 1		
	trial 2				trial 2		
	trial 3				trial 3		
h				h			
Q2	trial 1			Q2	trial 1		
	trial 2				trial 2		
	trial 3				trial 3		
h				h			
Q3	trial 1			Q3	trial 1		
	trial 2				trial 2		
	trial 3				trial 3		
h				h			
Q4	trial 1			Q4	trial 1		
	trial 2				trial 2		
	trial 3				trial 3		
h				h			
b				Theta			

<u>Experiment 6</u>

Hydraulic Jump

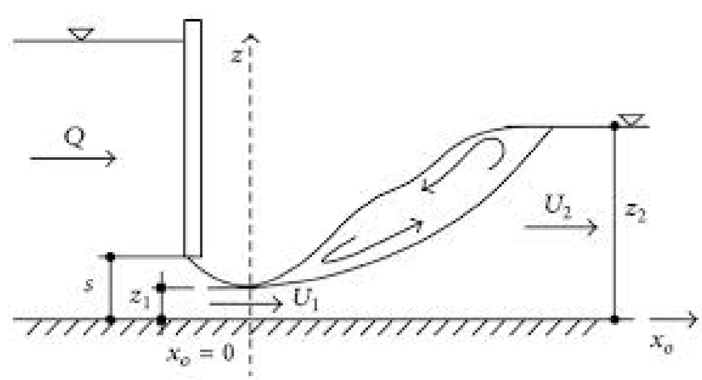
Objectives:

- Observe a standing Hydraulic Jump that forms between a super-critical flow section (generated through a gate) and a sub-critical section generated through a channel end gate).
- Measure heights before and after the hydraulic jump to compute conjugate depths. Measure the velocity to obtain flow velocity in the sub-critical section and derive the relationships for the HJ equation using continuity and momentum principles.

Background:

Hydraulic jumps mostly occur naturally in open channels. They are very efficient in dissipating the energy of the flow to make it more controllable and less erosive. In a hydraulic jump the flow goes from supercritical (high velocity) to subcritical (low velocity) regime. In fact, occasionally it might be necessary to create a jump to consume the excessive energy. For instance when water flows down from an outlet of an arch dam, it carries an enormous amount of kinetic energy, which might damage the receiving channels. To avoid damage, a hydraulic structure called stilling basin is built underneath the dam. This structure produces a controlled hydraulic jump, where the damaging energy is lost in the transition from supercritical to subcritical.

Set up:



Experimental Procedure

A hydraulic jump has been established in the elevated flume of the Hydraulics Laboratory. The following tasks must be accomplished in this experiment:

- Measure the width of the channel;
- Measure the sequent depths of the jump;
- Measure the flow depth upstream from the jump (subcritical region);
- Estimate the flow velocity in the subcritical region of the flow;
- Choose two points in the channel in the subcritical region downstream from the jump and measure their distance;
- Put a piece of paper on the flow surface and measure the time it takes for the paper to travel from one point to the other. Repeat this procedure three times and take the average travel time;
- Divide the distance by the average travel time to approximate the flow velocity at the water surface;

Data Analysis

1. Compute the average velocity.
2. Estimate the flow rate.
3. Estimate the critical depth.
4. Estimate the Froude number before and after the jump.
5. Using the initial depth, approximate the sequent depth of the jump with the appropriate relations given in your text book and compare it with your measurement, find % error.
6. Repeat step 5 but use sequent depth to obtain the initial depth, find % error;
7. Estimate the energy loss in the jump.
8. Draw the specific force and energy curve. [Momentum equation: $M= y^2/2 + Q^2/(g*y*b^2)$; b is width, y is depth, g is gravity, Q is discharge.]

Specify the sequent depths on each curve and answer the following questions:

(a) Are the specific forces of the initial depth and the sequent depth exactly the same? Why?

(b) Is the energy loss that you obtain from the specific energy curve the same as the one in step 9? Why?

Remember, mention sources of error in your lab!!

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Experiment 7

Outfall Diffuser

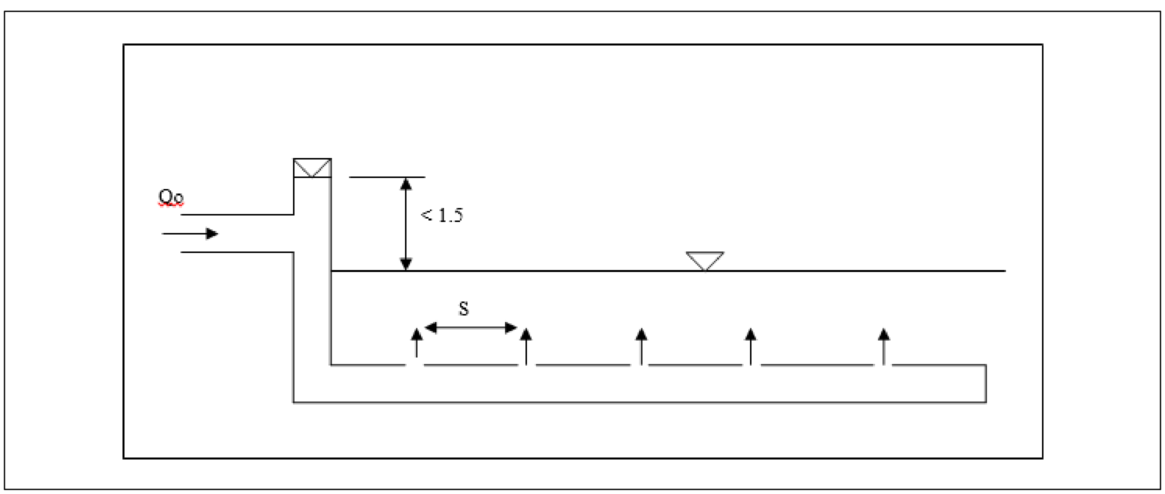
Objectives:

- Observe a standing Hydraulic Jump that forms between a super-critical flow section (generated through a gate) and a sub-critical section generated through a channel end gate).
- Measure heights before and after the hydraulic jump to compute conjugate depths. Measure the velocity to obtain flow velocity in the sub-critical section and derive the relationships for the HJ equation using continuity and momentum principles.

Background:

In general, it is possible to specify the desired flow distribution in a multi-port distribution system and to solve for the required flow areas to achieve this distribution provided that the upstream energy in the system is known. However, for a diffuser, a range of discharges may be experienced and the upstream energy level is likely to be a variable as well. In addition, the construction of different sized orifices at each discharge point is generally not feasible from an economic point of view. Therefore, it is generally better to specify a given diameter for all the discharge orifices or at least a combination of only a few different orifice diameters and then to compute the flow distribution from the proposed system.

Set up:



Experimental Procedure

Prepare a computer program or spreadsheet, which calculates the distribution of flow in a diffuser pipeline. The following design parameters will be used in the analysis:

design discharge:	Q_o	Diffuser diameter:	DIA
# of orifices:	N	Spacing between Orif.:	S
Diffuser pipe friction:	F		

Discharge coefficient for orifice: $$c_d = 0.63 - 0.58\frac{v^2}{2gE}$$

in which v is the velocity (in the pipe) just upstream from the orifice and E is the difference between the total energy inside the pipeline and the static head outside.

The analysis should begin with an assumed energy head at the upstream end of the diffuser and proceed downstream with repeated applications of orifice and energy equations. The repeated calculations will include the following steps:

1. Calculation of the orifice c_d based on local conditions.
2. Calculation of orifice flow, $Q_i = c_d A_i \sqrt{2gE}$.
3. Calculation of velocity in the pipe downstream from the orifice.
4. Calculation of the friction loss to the next orifice.
5. Calculation of the velocity head and energy at the next downstream orifice.

The repeated calculations will yield a total orifice discharge associated with the assumed upstream energy. Adjustments in this energy will then be necessary until the computed discharge agrees with the design discharge, while satisfying the following constraints:

1. The flow rates from the orifices must be within 7% of each other.
2. At the design discharge, the available head at the upstream end of the manifold cannot exceed a specific value.

Questions:

Prepare a brief description of the computations including a description of the input and output. Details of the computations must be submitted with the attached output to show your solution. The output must include the orifice diameters and the flow distribution from the orifices. Also, provide a listing of the required energy head at the upstream orifice to develop this flow condition. It is also useful to print out the maximum and minimum orifice discharges. Repeat the analysis for a flow rate of 0.5 m^3/s to see how changing the rate affects the flow distribution. Comment on all relevant results.

Data:

Q_0 = 5.0 m^3/s; DIA = 2.0 m; F = 0.02; S = 3.0 m; N = 40;
allowable upstream head difference = 1.5 m.

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Experiment 8

Water Distribution Network

Objectives:

- Use principles of kinetic and potential energy together with conservation of mass and principles of parallel and pipes in series to learn about how water loops and distributes itself in branched systems.
- Use a commercial software package (Water GEMS from Bentley Publishers, Computer Applications in Hydraulic Engineering, 8th Ed.) to design a water distribution network. with sources, demands, and run time scenarios for a "real" system with varying elevations. Use alternative solutions to find an optimum design in terms of required pipe diameters and also the necessary network devices such as valves and manholes.

Background:

This program is commercial grade and gives you a great introduction into working with real-world water distribution systems. While the student version is limited in terms of what size of project you can actually analyze it provides you with all the bells and whistles that the full license program makes available. We recommend that you work through the Tutorial #1 (Bentley book page 236) to get you familiar with the system.

Set up:

For this term please work on the following problem:

Problem #4 in chapter 6.10 of Bentley book

Procedure

We expect:

- That every student executes this experiment.
- That you submit a regular group lab report in which you answer all the questions of the problems and also submit graphs and maps of the problem set up.
- That the report reflects (somehow; be creative) the 5 individual efforts.