Experiment (13): Flow channel

Introduction:

An open channel is a duct in which the liquid flows with a free surface exposed to atmospheric pressure. Along the length of the duct, the pressure at the surface is therefore constant and the flow can not be generated by external pressures but only by differences in potential energy due to the slope of the surface.

The flow channel is one of the most important tools available for the teaching of hydraulic principles. The flow channel has been designed to allow students a wide range of experiments on water flow in an open channel under different flow conditions and analyze the effects of test models of various shapes on water flow. It also allows the verification of the Chezy equation and Mannings friction factor. In addition studies of 'specific energy-depth' relationships, the effect of various weirs and flumes, hydraulic jump and the determination of hydraulic mean depth can also be carried out.

Flow channel:

Flow channel is designed to allow a series of experiments on water flow through a rectangular channel to be conducted. The channel is of rectangular cross section 175mm high x 55mm wide and 2500mm long. The flow channel incorporates a specially designed entry section which incorporates a stilling pond, filled with glass spheres, to provide smooth non turbulent flow conditions at entry to the channel. At the discharge end of the channel an adjustable undershot sluice gate is provided which can be used to control the exit flow.

The channel is supported on a steel framework which incorporates a variable height support at the right hand end allowing the slope of the channel to be varied. A measuring point is provided together with a clock distance gauge and the calibration is such that 1 revolution of the clock dial is equivalent to a slope of 1 :1500.

Figure 1: Flow channel apparatus

Exercise A (Flow in open channels)

Purpose:

To investigate the flow of water through a rectangular open channel.

Apparatus:

1. Flow channel.
2. Hydraulics bench to supply water to the flow channel apparatus (the flow of water can be measured by timed volume collection).

Theory:

Consider an open channel of uniform width B and with a flat but sloping bed as illustrated below, in which a liquid flows from left to right.

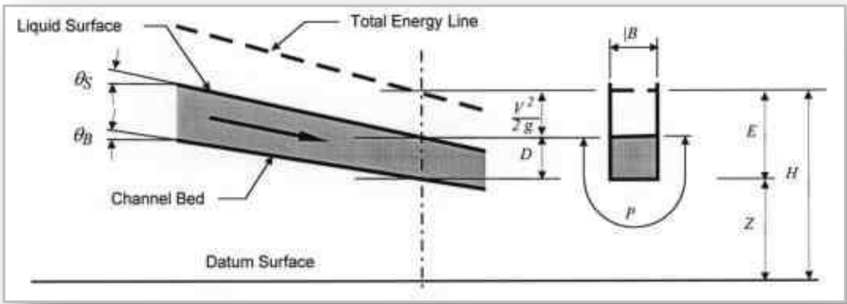

Figure 2: Rectangular open channel

At plane X let the
Height of the channel bed above datum = Z
Depth of liquid in the channel = D
Width of the channel = B
Wetted perimeter = P = $B + 2D$
Mean velocity of the liquid = V
The hydraulic mean radius R_h is defined as:

$$R_h = \frac{A}{P} = \frac{B.D}{B + 2D}$$

Applying Bernoulli's equation to the liquid at plane X then the total energy head above the datum is:

$$H = Z + D + \frac{V^2}{2g}$$

It is often advantageous to use the channel bed as the datum. The total energy head above the channel bed is known as the specific energy, E is:

$$E = D + \frac{V^2}{2g}$$

Rearranging to obtain the mean velocity:

$$V = \sqrt{2g(E - D)}$$

Depending on the slope of the channel, the depth of the liquid along the channel may be constant or it may either decrease or increase. Consideration of continuity of flow rate between two planes X_1 and X_2 requires that the flow rate Q is the same at each of the planes so that:

$$Q = A_1 . V_1 = A_2 . V_2$$

and for a rectangular channel of uniform width B:

$$q = \frac{Q}{B} = V_1 D_1 = V_2 D_2$$

For a uniform or steady flow in a constant width channel the depth of liquid will be constant along the length of the channel D_1=D_2 and therefore the slope of the surface S_S must be parallel to the slope of the bed S_B so that $S_S = S_B$.

If the velocity along the bed increases then the depth decreases in the direction of flow $D_1 > D_2$ and the slope of the surface is greater than the slope of the channel bed $S_S > S_B$ or if the velocity decreases then the depth increases $D_1 < D_2$ and $S_S < S_B$.

Consider the case of constant flow, a mean velocity V in a rectangular duct can be calculated using Chezy formula:

$$V = C\sqrt{R_h S_B}$$

where C is the Chezy coefficient for the channel.

The Manning formula is used exclusively for open channels and is usually used in large civil engineering applications. Whilst the formula of Darcy-Weisbach and Colebrook-White applied to channels are derived from flow in circular and non-circular pipes which are more suited to mechanical engineering problems.

From the study of frictional forces in pipes, the friction factor is found to be dependent on the Reynolds number and on the relative roughness of the pipe wall, however for very rough pipes the friction factor becomes independent of Reynolds number and depends only on the roughness of the pipe wall. For many open channels found in civil engineering problems the channel walls are very rough and in studying these civil engineering channels Robert Manning found from experimental work that the Chezy coefficient varied as the sixth root of the hydraulic mean radius and inversely to the roughness of the channel.

$$C = \frac{R_h^{1/6}}{n}$$

Where n is the Manning roughness factor.

The velocity in an open channel is given by the Manning formula:

$$V = C\sqrt{R_h S_B} = \frac{R_h^{2/3} S_B^{1/2}}{n}$$

Typical values of Manning's roughness factor with units of $m^{1/2}$ and sec^{-1} are:

Irregular rock channels	0.035 to 0.045
Rough earth channels	0.025 to 0.040
Smooth earth channels	0.017 to 0.025
Rubble masonry	0.017 to 0.03
Clean smooth brick or wood channels	0.010 to 0.017
Smooth metal channels	0.008 to 0.010

General experimental procedures:

1. Position the flow channel to the left hand side of the hydraulics bench so that the discharge from the flow channel will enter the weir channel of the hydraulics bench.
2. Adjust the feet of the flow channel support frame so that it does not rock.
3. Connect the delivery hose from the hydraulics bench to the inlet connection of the flow channel.
4. Lower the sluice gate at the discharge end of the tunnel to seal the exit from the tunnel.
5. Start the hydraulics bench pump and allow water to enter the channel until it is filled to a depth of approximately 20mm.
6. Measure the distance of the water level from the top edge of the channel wall at each end and by means of the slope adjusting knob, make the measurements equal.
7. Set the clock dial to zero and note the reading of the dial counter gauge.
8. Check that the depth of water in the channel is constant along the length of the channel. This is the setting for zero slope.

Procedures:

1. Set up the hydraulics bench using the general experimental procedures.
2. Fully raise the sluice gate at the discharge end of the channel so that it will not restrict the flow.
3. Set the flow channel slope to a downwards gradient from left to right of 1·25 in 1500 i.e. 1¼ revolutions of the clock dial from the zero point.
4. Start the hydraulics bench pump and adjust the flowrate to approximately 1·5 liters/sec.
5. When the flow conditions have become stable measure the flow rate using the volumetric tank of the hydraulics bench and measure the depth of water in the flow channel at 50cm from the left hand end.
6. Keeping the flow rate constant flow repeat the above measurements for the following different downward gradients.

Slope	Revs. on dial from 'zero slope'
1.7/1500	$1^{7/10}$
1.8/1500	$1^{8/10}$
2.5/1500	$2^{1/2}$
3.0/1500	3
4.0/1500	4
5.5/1500	$5^{1/2}$

Results and analysis:

1. Record the results on a copy of the results sheet.
2. For each value of slope of the channel calculate:-
   - The water flow rate Q
   - The flow area from $A = B.D$
   - The mean velocity from $V = Q/A$
   - The hydraulic mean radius from $R_h = A/(2D + B)$
   - The slope of the channel bed S_B
   - The expression $R_h^{2/3} S^{1/2}$
3. Plot a graph of the mean velocity V against $R_h^{2/3} S^{1/2}$ and determine the Manning roughness value from the slope of the graph.

Conclusion:

Comment on the value of Manning's roughness coefficient n and compare it with values quoted in text books.

Exercise B (Flow under a sluice gate)

Purpose:

To investigate the flow of water under a sluice gate.

Apparatus:

1. Flow channel.
2. Hydraulics bench to supply water to the flow channel apparatus (the flow of water can be measured by timed volume collection).

Theory:

By applying Bernoulli's equation to the flow in a channel it was shown that the specific energy measured from the bed of the channel at any plane is given by:

$$E = D + \frac{V^2}{2g} = D + \frac{Q^2}{2gA^2}$$

the mean velocity is:

$$V = \sqrt{2g(E - D)}$$

and the discharge is:

$$Q = A\sqrt{2g(E - D)}$$

Substituting $B \cdot D$ for A in the specific energy equation and defining q as the volume flow per unit of channel width so that $q = Q/B$

$$E = D + \frac{Q^2}{2gA} = D + \frac{q^2}{2gD^2}$$

Now differentiating with respect to depth and equating to zero to determine the conditions for the minimum value of the specific energy E_C:

$$D_C = \sqrt[3]{\frac{q^2}{g}}$$

$$E_C = \frac{3}{2} D_C$$

The critical depth corresponding to minimum specific energy is:

$$D_C = \frac{2}{3} E_C$$

and the velocity at this critical conditlon is:

$$V_C = \sqrt{2g(E_C - D_C)} = \sqrt{2g(E_C - \frac{2}{3} D)} = \sqrt{g.D_C}$$

For a given value of discharge q there will be two possible depths for a given value of specific energy as shown in the graph below.

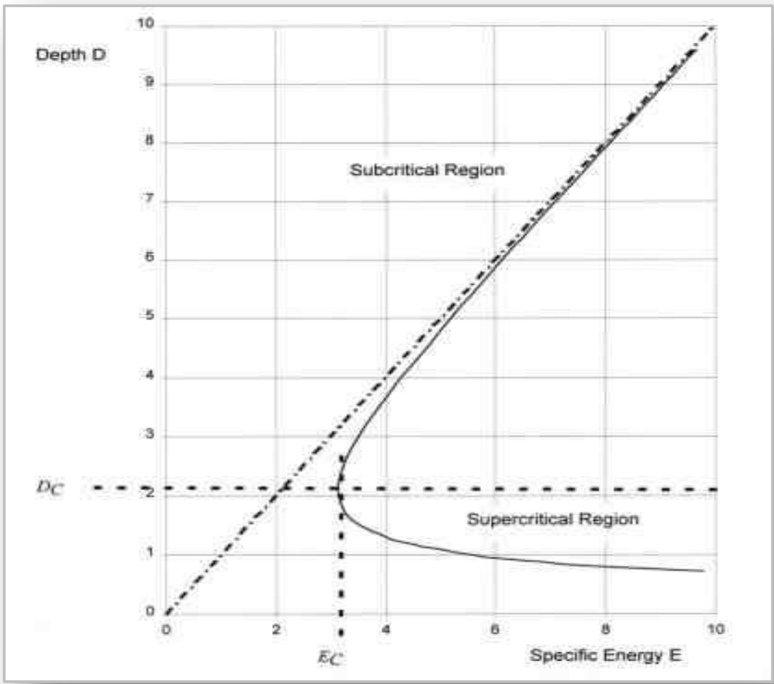

Figure 3: Specific energy-depth curve

For depths greater than the critical depth, the flow is said to be sub critical or tranquil and for depths less than the critical depth, the flow is described as supercritical or shooting.

The flow under a sluice gate is dependent on the upstream head and the height under the sluice gate.

Assuming tranquil conditions upstream, the flow under the sluice gate may be either tranquil or supercritical, if it is supercritical then a downstream hydraulic jump can occur if the slope is either insufficient to maintain the supercritical flow or if there is a downstream restriction.

a) Free discharge – Unrestricted downstream **b) Flooded discharge – Downstream restricted**

Figure 4: Flow under a sluice gate

Procedures:

1. Set up the hydraulics bench using the general experimental procedures.
2. Fit the sluice gate in the channel at a distance of 50cm or more from the water flow entry.
3. Fully raise the sluice gate at the discharge end of the channel so that it will not restrict the flow ..
4. Turn on the hydraulics bench and adjust the water flow to approximately 1·5 liter/second.
5. Check that stable conditions are achieved at the upstream measuring point (20cm upstream

from the sluice gate) and when stable flow conditions are established in the channel measure the water depth:

- 20cm upstream of sluice gate.
- 10cm downstream of sluice gate.
- 20cm downstream of sluice gate.

6. Check the width of the flow channel at each of the three measuring points.

Results and analysis:

Record the results on a copy of the results sheet.

1. Calculate the water flow rate.
2. Calculate the specific energy for each of the three measurement points from: $E = D + \frac{Q^2}{2gA^2}$
3. Calculate the critical point using: $D_C = \sqrt[3]{\frac{q^2}{g}}$ and $E_C = \frac{3}{2}D_C$
4. Draw a graph of depth D against specific energy E for the three measured points and for the calculated critical point. Draw a smooth curve through the four points.
5. Superimpose on to the graph a line from the origin at a slope of $\frac{2}{3}$ to represent $D_C = \frac{2}{3}E_C$

Conclusion:

Discuss the shape of the graph of depth against specific energy.

Exercise C (Demonstration of a hydraulic jump)

Purpose:

To investigate the phenomenon of a hydraulic jump.

Apparatus:

1. Flow channel.
2. Hydraulics bench to supply water to the flow channel apparatus (the flow of water can be measured by timed volume collection).

Theory:

If the flow in a channel is supercritical and there is insufficient slope for the gravity forces to overcome the frictional forces then the flow will suddenly change to a sub critical flow by means of a hydraulic Jump which is illustrated in the figure below.

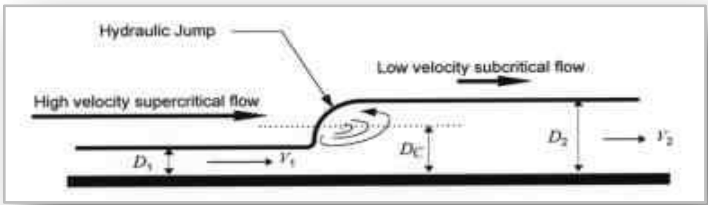

Figure 4: Hydraulic jump

The depth of water before the jump is less than the critical depth and the depth after the hydraulic jump is greater than the critical depth. The specific energy before and after the hydraulic jump must be higher than the critical energy value. The hydraulic jump is a highly irreversible process, there is a loss in kinetic energy, and although there is a gain in potential energy, the irreversibility of the process requires that the specific energy downstream of the hydraulic jump is less than the specific energy upstream of the hydraulic jump. A hydraulic jump will occur in a supercritical flow if the downstream water level is raised above the critical depth by an obstruction.

For continuity of flow through the hydraulic jump:

$$Q = BD_1V_1 = BD_2V_2$$

$$V_2 = V_1\frac{D_1}{D_2}$$

In a hydraulic jump, the velocity changes from V_1 to V_2 and hence there is a change in momentum through the jump. The force producing this change in momentum is due to the difference in hydrostatic pressure resulting from the change of depth.

By equating the resultant hydrostatic force to the rate of change of momentum, the conjugate depth D_2 can be calculated from the initial depth D_1 from the following relationship:

$$D_2 = -\frac{D_1}{2} + \sqrt{\frac{2V_1^2D_1}{g} + \frac{D_1^2}{4}}$$

The loss of specific energy due to irreversibility in a hydraulic jump can be calculated as the following:

$$H_L = E_1 - E_2 = \frac{(D_2 - D_1)^3}{4D_1D_2}$$

Procedures :

1. Set up the flow channel as for exercise B.
2. Fully raise the sluice gate at the discharge end of the channel so that it will not restrict the flow.
3. Turn on the hydraulics bench and adjust the water flow to approximately 1·5 liter/second.
4. Adjust the height of the sluice gate fitted to the discharge end of the flow channel until the bottom of the sluice gate just touches the water surface.
5. A hydraulic jump will then form, make fine adjustments to the discharge sluice gate until a stable stationary position of the hydraulic jump is obtained between the two sluice gates.
6. Measure the water depth each side of the hydraulic jump.

Results and analysis:

1. Record the results on a blank copy of the results sheet.
2. Calculate the water flow rate.
3. Calculate the specific energy for each of the three measurement points from: $E = D + \frac{Q^2}{2gA^2}$
4. Provided that the flow rate is unchanged from that for expercise B, superimpose on the graph for exercise B the two points for the depth and specific energy before and after the hydraulic jump.

Conclusion:

Discuss the shape of the water surface before and after the hydraulic jump.