57:020 Mechanics of Fluids and Transfer Processes

ROUTINE LABORATORY INSTRUMENTS FOR THE MEASUREMENT OF THE MAIN FLUID MECHANICS QUANTITIES

In this section, the underlying principles, characteristics and operation of the most common fluid measuring devices used throughout the laboratory activity are described.

1. Liquid Level Measurement

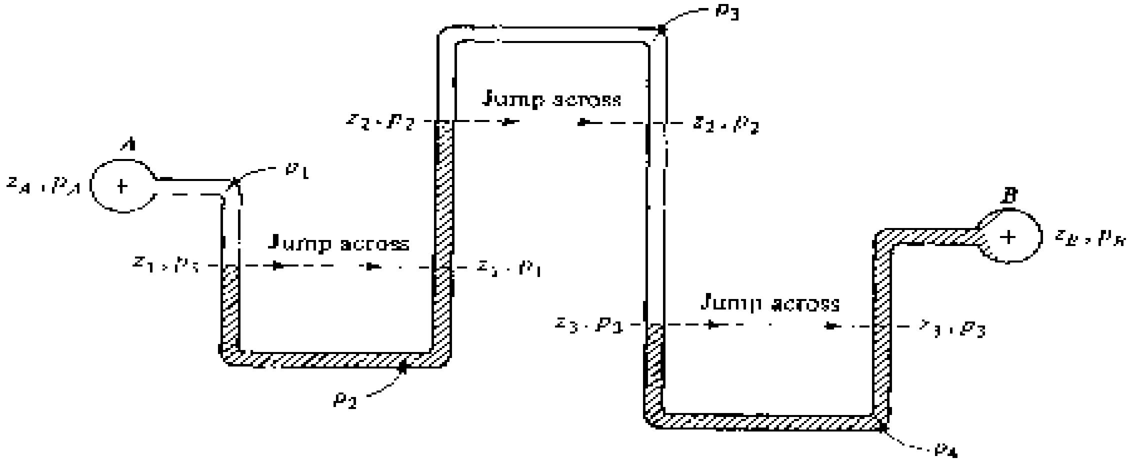
Usually these measurements are associated with free-surface or stationary flows. **Scales and tapes** for the measurement of length are readily available in a variety of forms.

A type of linear measurement peculiar to the fluids laboratory is the measurement of surface level in an open channel. This measurement is accomplished in general by means of a **point gage**. The gage is comprising a pointed shaft or hook mounted on a graduated rod which can be moved vertically relative to a zero line. Further precision can be gained by means of a vernier (see Figure 2) which allows to make readings with a precision of 0.001 ft. Contact with the surface is best observed in the reflection of light.

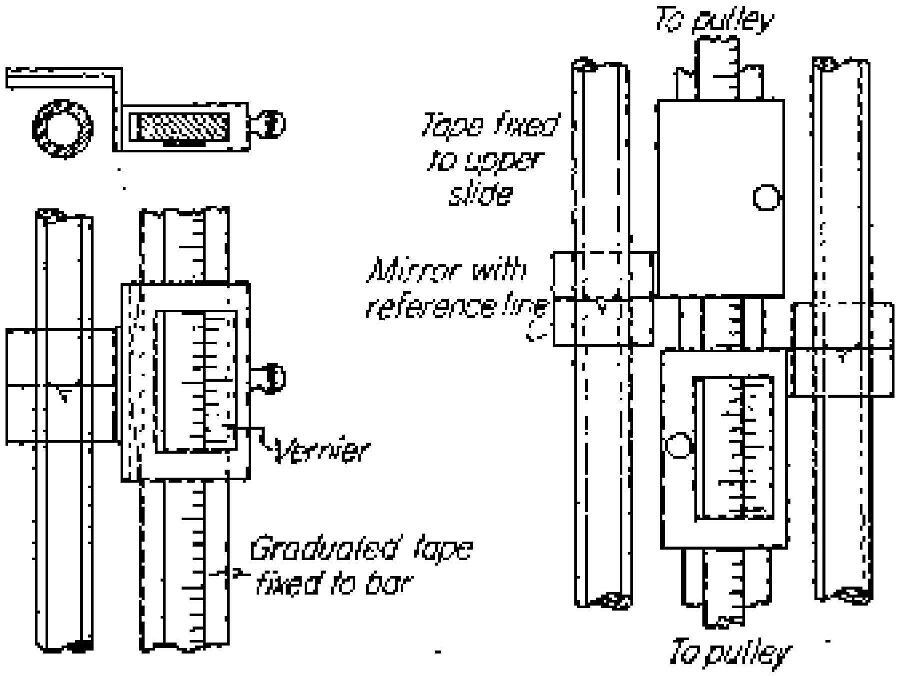
In zone of hydrostatic pressure, the liquid level can be determined by connecting a conveniently located **piezometer or open manometer** (open tubes for measurement of the pressure head of liquids) or a **stilling well** with point gage. Both methods remove difficulties associated with the waviness of the free surface.

2. Pressure Measurement

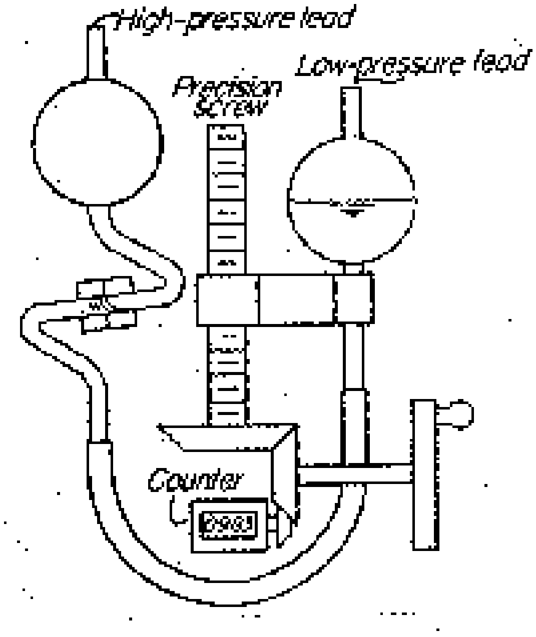
The simplest instruments for pressure measurement are the **single-column manometers**. They measure the pressure head relative to some arbitrary datum. Most often it is the difference between two levels or heads in a static or moving stream that is to be measured. Then rather to make two separate readings and subtract one from the other, we use the **differential manometer** which yield a single differential reading. Differential manometers relate a pressure difference to the densities and the elevations of liquid columns into a U-tube. The configuration of such a manometer is shown in Fig 1.



By repeated application of the hydrostatic formula we can relate the pressures p_A and p_B to the densities and the levels of the fluid levels in the tubes. Usually the central columns are placed on the sides of the same guide bar. Separate slides are provided for each column, and the graduated scale is fixed to one and read by the vernier on the other as shown in Figure 2.

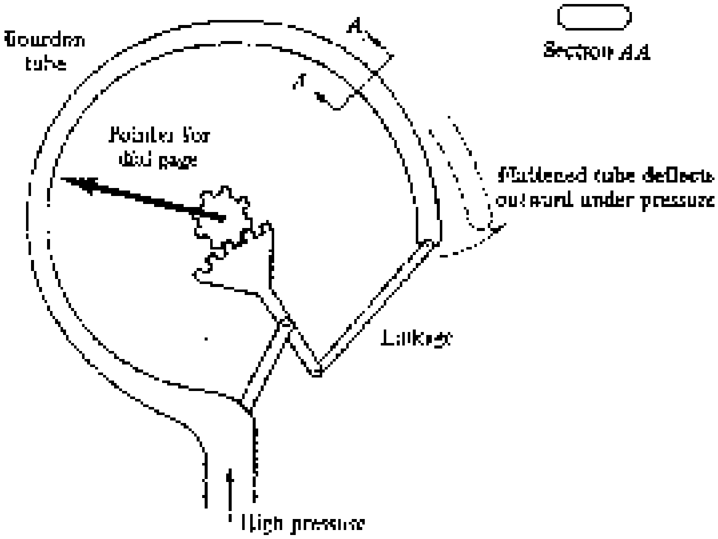


For small pressure differences (e.g., measurements in gas) the augmentation of the manometer sensitivity is accomplished by using a **sloping manometer** (inclined manometer) to magnify the displacement of the fluid meniscus. H. Rouse, former IIHR scientist, also designed a manometer from this category (see Figure 3).



For higher pressures, as is the case in pressure-driven flows (duct flows) **bourdon-tube pressure gages** are used. A curved tube, as shown in see Figure 4, with a flattened cross section will deflect outward when pressurized internally.

The deflection can be measured by a linkage attached to a calibrated dial-gage pointer. Extreme accuracy can be obtained through proper design, and commercial bourdon gages are available with an accuracy of ± 0.2 percent of full scale.

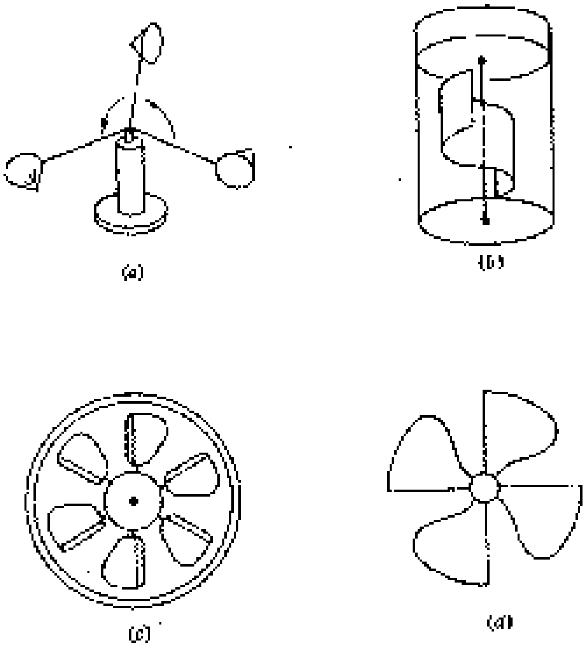


3. Velocity Measurement

Velocity, the magnitude of which is a simple combination of length and time scales, is sometimes **determined directly** as such. For example, by timing a **float** over a known distance the average rate of displacement at the free surface can be computed. More significantly, exposure of a camera for a short time interval will permit the measurement of streaks made on the film by surface floats or suspended particles in the flow (e.g., small neutrally buoyant spheres or hydrogen bubbles) to indicate local displacement in the given interval.

There are also various **indirect means** of velocity indication depending upon one or another of its effects. The simplest among them are the **mechanical rotating devices** and instruments employing Bernoulli relationship: **Pitot-tube and obstruction meters**. As the last mentioned instruments are usually used for metering the flow, they will be presented in the next section.

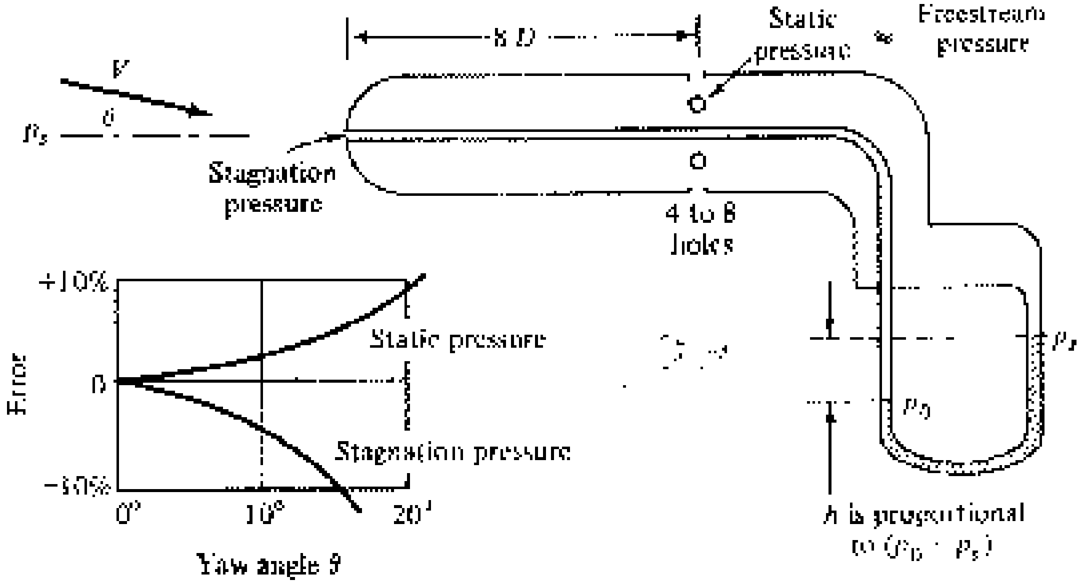
Rotating sensors, see Figure 5, can be used in either gases or liquids, and their rotation rate is approximately proportional to the flow velocity.


(a) (b)

(c) (d)

Calibration is needed to relate rotational speed against linear speed. Some of them rotate always in the same way (e.g., **cup anemometer, Savonius rotor**) regardless of flow direction. Others, can sense reverse flow, but must be aligned with the flow to be measured parallel to their axis of rotation (**duct-propeller** and **free-propeller meters**). All these rotating sensors can be attached to counters or sensed by electromagnetic or slip-ring devices for either a continuous or digital reading of flow velocity. All the above described flow meters have the disadvantage of being relatively large and thus not representing a "point".

By far the most common laboratory instrument for velocity measurement is the Pitot tube shown in Figure 6.



A slender tube aligned with the flow can measure local velocities by means of pressure difference. It has side-wall holes to measure the static pressure p_s in the moving stream, and a hole in the front to measure the stagnation pressure p_0, where the stream is decelerated to zero velocity. Instead of measuring these pressures separately, it is customary to measure their difference with, say, a differential manometer. For Re_D >1000, where D is the probe diameter, the flow around the probe is nearly frictionless and Bernoulli's relation for incompressible flows applies with good accuracy

$$p_s + \frac{1}{2} r V^2 + rgz \approx p_0 + \frac{1}{2} r(0)^2 + rgz_0 \qquad (1)$$

Assuming that he elevation difference is negligible (1) reduces to

$$V = \left[\frac{2(p_0 - p_s)}{r} \right]^{1/2} \qquad (2)$$

The primary disadvantage of the Pitot tube is that it must be aligned with the flow direction, which may be unknown. For yaw angles greater than 5°, there are substantial errors in both the measurement of p_s and p_0 , as shown in Figure 6.

Pitot tube is useful in fluids and gases. For gases compressibility correction is necessary. Because of the slow response of the fluid-filled tubes leading to the pressure sensors, it is not useful for unsteady-flow measurements. Also, it is not suitable for low-velocity measurements in gases because of the small-pressure differences developed.

4. Flow Rate Measurement

Almost all practical fluids engineering problems are associated with the need for an accurate flow measurement. The methods used for the measurement of mass or volume-flow rate are distinct for the free-surface flows from those used for duct flows.

Among the most common laboratory instruments used to measure the integrated mass, or volume flow passing through a duct are those from the mechanical and head-losses classes. The mechanical instruments measure actual mass or volume of fluid by trapping it and counting it. The instruments using the head-losses are relating the pressure drop in the device to the flow flux passing through it.

The **time-weight measurement of volume flow rate** (steady flow) is a procedure which is performed frequently throughout the semester activity. This measurement requires a container to capture the entire flow, a scale to measure the weight of the container and the captured fluid, and a stop-watch to measure the time it takes to capture a given weight of fluid. The mass flow rate and the volume flow rate issued by a conduit in a given time Δt is given by

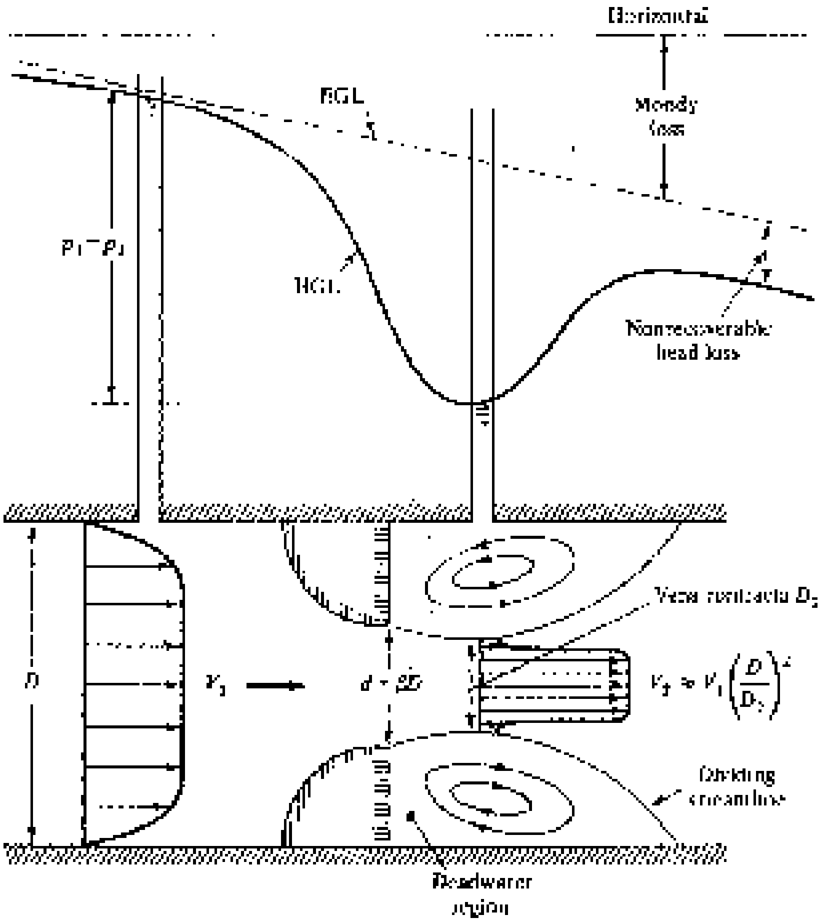
$$\overset{\bullet}{m} = \frac{W}{g\Delta t} \quad ,$$

and, respectively, (3)

$$\overset{\bullet}{V} = \frac{W}{g\Delta t}$$

where W the weight of the issued fluid, r is the density of the fluid, and $g = rg$ is the specific weight of the fluid. The most accurate measurement for a given weighing tank is made with the largest weight and Δt possible.

Bernoulli obstruction theory. Consider the generalized flow obstruction shown in Figure 7.

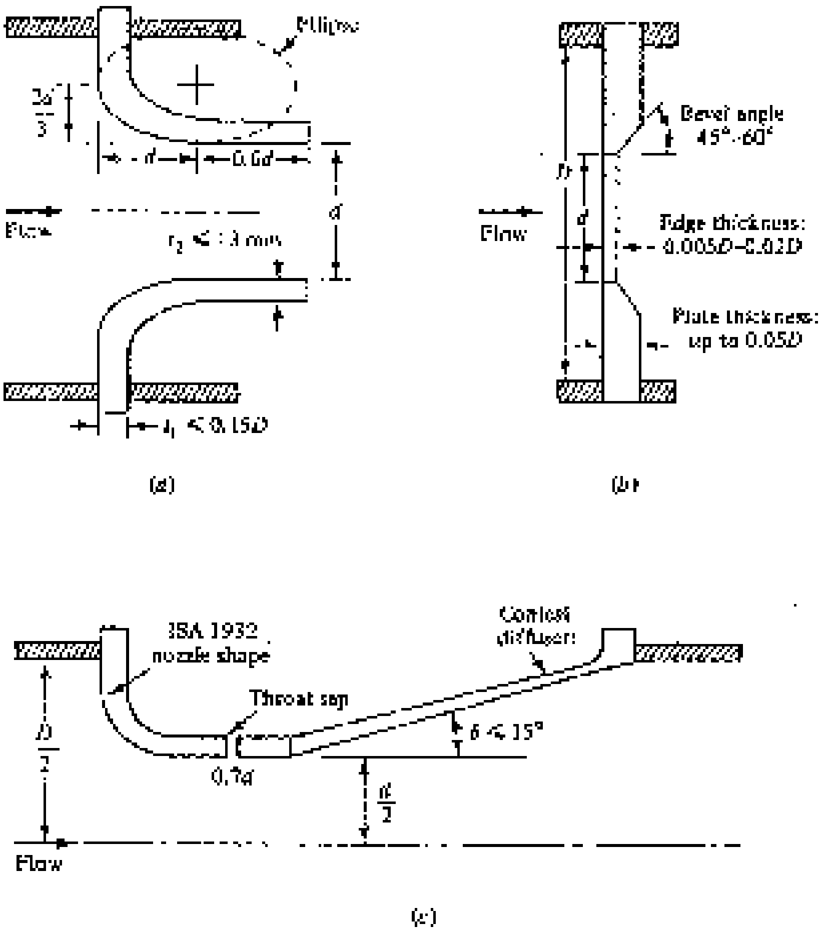


The flow in the basic duct of diameter D is forced through an obstruction of diameter d; the b ratio of the device is a key parameter, $b = d/D$. Applying Bernoulli and continuity equations for incompressible steady frictionless flow, and then calibrating the device we can get a relationship between the discharge Q and the pressure change (p_1-p_2) in the form

$$Q = C_d A_t \left[\frac{2(p_1 - p_2)/r}{1 - b^4} \right]^{1/2} = a A_t \left[\frac{2(p_1 - p_2)}{r} \right]^{1/2} \qquad (4)$$

where A_t is the section of the throat, $C_d = \mathrm{f}(b, Re_D = V_1 D/n)$ is the discharge coefficient, and $a = \mathrm{f}(b, Re_D)$ is the dimensionless flow coefficient. Since the design parameters are assumed known, the correlations for a or C_d are the only one to be determined.

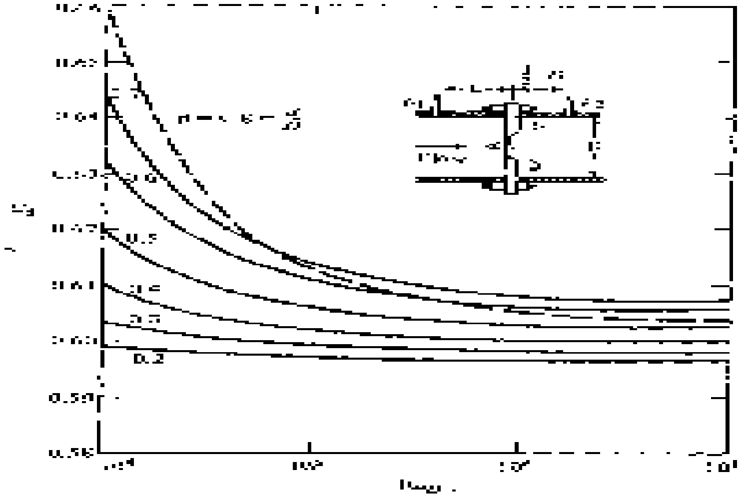
The mass flow rate is related to Q by $\dot{m} = rQ$. Figure 8 shows the three basic devices recommended for use by the International Organization for Standardization (ISO), the long radius nozzle, the thin-plate orifice, and the venturi nozzle. Figure 9 shows a sample of discharge coefficient chart available for instrumentation designers.



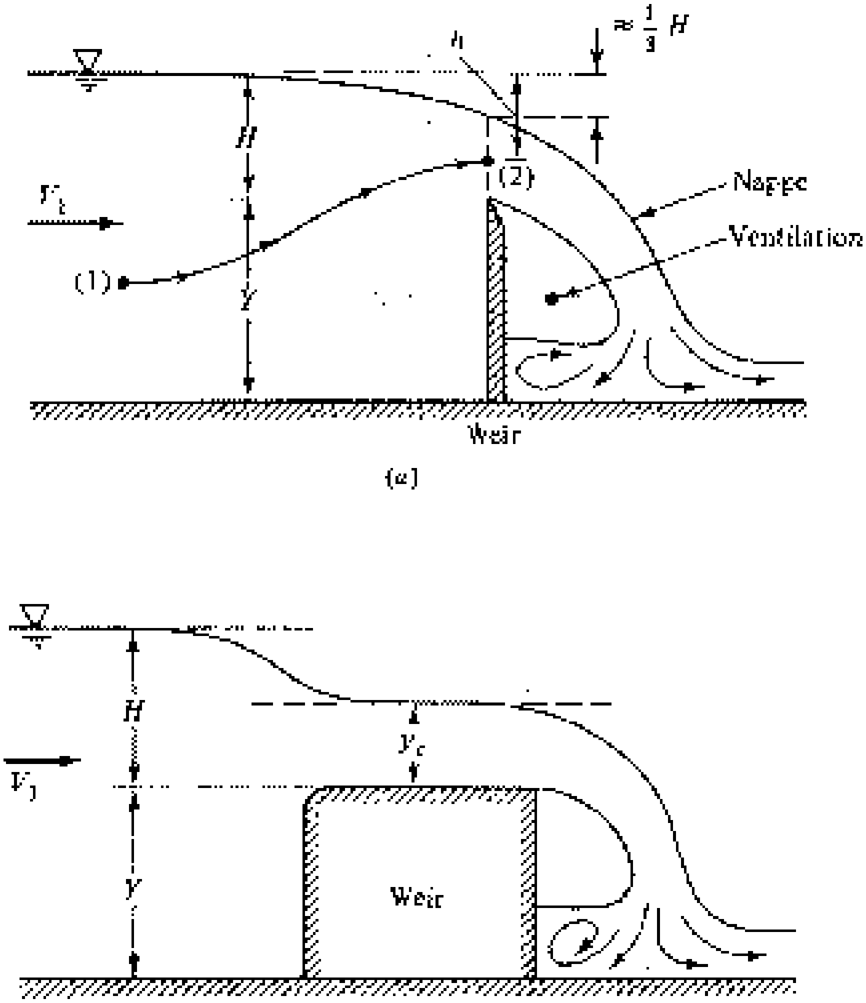
(a)

(b)

(c)



Weirs are obstructions in the bottom of a channel which the flow must deflect over. A weir, is essentially an open-channel version of an orifice-plate meter. They are frequently selected to measure the flow rates in laboratory free-channel flows because they have a simple design and are effective flowmeter. A sharp-crested and a broad-crested weirs are schematically shown in Figure 10.



(a)

(b)

For certain simple geometry channels, the discharge *Q* correlates with the blockage height (the head *H* on the weir) to which the upstream flow is deflected in the presence of the weir through a relationship of the form

$$Q = k\,H^n \qquad (5)$$

where *k* and *n* are coefficients dependent on the weir geometry. These coefficients are calculated or obtained through calibration.