Part 1 Basic Principles of Open Channel Flows

Introduction 1

Summary

The introduction chapter reviews briefly the basic fluid properties and some important results for fluids at rest. Then the concept of open channel flow is defined and some applications are described.

1.1 PRESENTATION

The term 'hydraulics' is related to the application of the Fluid Mechanics principles to water engineering structures, civil and environmental engineering facilities, especially hydraulic structures (e.g. canal, river, dam, reservoir and water treatment plant).

In the book, we consider open channels in which liquid (i.e. water) flows with a free surface. Examples of open channels are natural streams and rivers. Man-made channels include irrigation and navigation canals, drainage ditches, sewer and culvert pipes running partially full, and spillways.

The primary factor in open channel flow analysis is the location of the free surface, which is unknown beforehand (i.e. *a priori*). The free surface rises and falls in response to perturbations to the flow (e.g. changes in channel slope or width). The main parameters of a hydraulic study are the geometry of the channel (e.g. width, slope and roughness), the properties of the flowing fluid (e.g. density and viscosity) and the flow parameters (e.g. velocity and flow depth).

1.2 FLUID PROPERTIES

The *density* ρ of a fluid is defined as its mass per unit volume. All real fluids resist any force tending to cause one layer to move over another, but this resistance is offered only while the movement is taking place. The resistance to the movement of one layer of fluid over an adjoining one is referred to as the *viscosity* of the fluid. Newton's law of viscosity postulates that, for the straight parallel motion of a given fluid, the tangential stress between two adjacent layers is proportional to the velocity gradient in a direction perpendicular to the layers:

$$\tau = \mu \frac{\mathrm{d}V}{\mathrm{d}y} \tag{1.1}$$

where τ is the shear stress between adjacent fluid layers, μ is the dynamic viscosity of the fluid, V is the velocity and y is the direction perpendicular to the fluid motion. Fluids that obey Newton's law of viscosity are called *Newtonian fluids*.

At the interface between a liquid and a gas, a liquid and a solid, or two immiscible liquids, a tensile force is exerted at the surface of the liquid and tends to reduce the area of this surface to the greatest possible extent. The *surface tension* is the stretching force required to form the film: i.e. the tensile force per unit length of the film in equilibrium.

The basic properties of air and water are detailed in Appendix A1.1.

Notes

1. Isaac Newton (1642–1727) was an English mathematician.
2. The kinematic viscosity is the ratio of viscosity to mass density:

$$\nu = \frac{\mu}{\rho}$$

3. A Newtonian fluid is one in which the shear stress, in one-directional flow, is proportional to the rate of deformation as measured by the velocity gradient across the flow (i.e. equation (1.1)). The common fluids such as air, water and light petroleum oils, are Newtonian fluids. Non-Newtonian fluids will not be considered any further in Part I. They will be briefly mentioned in Part II (i.e. hyperconcentrated flows).

Application

At atmospheric pressure and 20°C the density and dynamic viscosity of water are:

$$\rho_w = 998.2\,\text{kg/m}^3$$

$$\mu_w = 1.005 \times 10^{-3}\,\text{Pa s}$$

and the density of air is around:

$$\rho_{air} = 1.2\,\text{kg/m}^3$$

Water in contact with air has a surface tension of about 0.0733 N/m at 20°C.

Considering a spherical gas bubble (diameter d_{ab}) in a liquid, the increase of gas pressure required to balance the tensile force caused by surface tension equals: $\Delta P = 4\sigma/d_{ab}$.

1.3 STATIC FLUIDS

Considering a fluid at rest (Fig. 1.1), the pressure at any point within the fluid follows Pascal's law. For any small control volume, there is no shear stress acting on the control surface. The only forces acting on the control volume of fluid are the gravity and the pressure[1] forces.

In a static fluid, the pressure at one point in the fluid has an unique value, independent of the direction. This is called Pascal's law. The pressure variation in a static fluid follows:

$$\frac{dP}{dz} = -\rho g \tag{1.2}$$

where P is the pressure, z is the vertical elevation positive upwards, ρ is the fluid density and g is the gravity constant (see Appendix A1.1).

[1] By definition, the pressure acts always normal to a surface. That is, the pressure force has no component tangential to the surface.

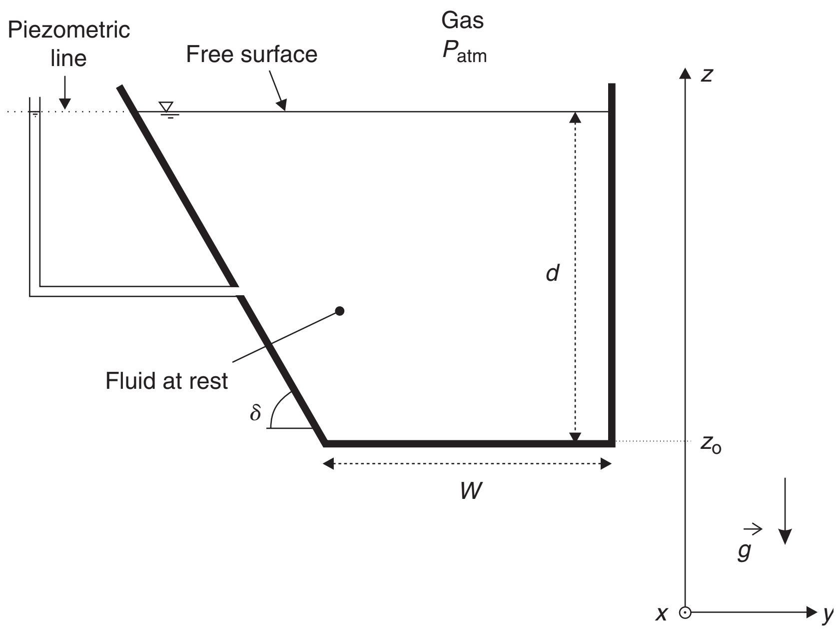

Fig. 1.1 Pressure variation in a static fluid.

For a body of fluid at rest with a free surface (e.g. a lake) and with a constant density, the pressure variation equals:

$$P(x,y,z) = P_{atm} - \rho g(z - (z_o + d)) \tag{1.3}$$

where P_{atm} is the atmospheric pressure (i.e. air pressure above the free surface), z_o is the elevation of the reservoir bottom and d is the reservoir depth (Fig. 1.1). $(d + z_o)$ is the free-surface elevation. Equation (1.3) implies that the pressure is independent of the horizontal co-ordinates (x, y). The term $\{-\rho g(z - (z_o + d))\}$ is positive within the liquid at rest. It is called the hydrostatic pressure.

The pressure force acting on a surface of finite area which is in contact with the fluid is distributed over the surface. The resultant force is obtained by integration:

$$F_p = \int P \, \mathrm{d}A \tag{1.4}$$

where A is the surface area.

Note

Blaise Pascal (1623–1662) was a French mathematician, physicist and philosopher. He developed the modern theory of probability. He also formulated the concept of pressure (between 1646 and 1648) and showed that the pressure in a fluid is transmitted through the fluid in all directions (i.e. Pascal's law).

Application

In Fig. 1.1, the pressure force (per unit width) applied on the sides of the tank are:

$$F_{\mathrm{p}} = \rho g d W \qquad \text{Pressure force acting on the bottom per unit width}$$

$$F_{\mathrm{p}} = \frac{1}{2}\rho g d^2 \qquad \text{Pressure force acting on the right-wall per unit width}$$

For the left-wall, the pressure force acts in the direction normal to the wall. The integration of equation (1.4) yields:

$$F_{\mathrm{p}} = \frac{1}{2}\rho g \frac{d^2}{\sin\delta} \qquad \text{Pressure force acting on the left-wall per unit width}$$

1.4 OPEN CHANNEL FLOW

1.4.1 Definition

An open channel is a waterway, canal or conduit in which a liquid flows with a free surface. An open channel flow describes the fluid motion in open channel (Fig. 1.2). In most applications, the liquid is water and the air above the flow is usually at rest and at standard atmospheric pressure (see Appendix A1.1).

Notes

1. In some practical cases (e.g. a closed conduit flowing partly full), the pressure of the air above the flow might become sub-atmospheric.
2. Next to the free surface of an open channel flow, some air is entrained by friction at the free surface. That is, the no-slip condition at the air–water interface induces the air motion. The term 'air boundary layer' is sometimes used to describe the atmospheric region where air is entrained through momentum transfer at the free surface.
3. In a clear-water open channel flow, the free surface is clearly defined: it is the interface between the water and the air. For an air–water mixture flow (called 'white waters'), the definition of the free surface (i.e. the interface between the flowing mixture and the surrounding atmosphere) becomes somewhat complicated (e.g. Wood, 1991; Chanson, 1997).

1.4.2 Applications

Open channel flows are found in Nature as well as in man-made structures (Fig. 1.3, Plates 1 to 32). In Nature, tranquil flows are observed in large rivers near their estuaries: e.g. the Nile River between Alexandria and Cairo, the Brisbane River in Brisbane. Rushing waters are encountered in mountain rivers, river rapids and torrents. Classical examples include the cataracts of the Nile River, the Zambesi rapids in Africa and the Rhine waterfalls.

Man-made open channels can be water-supply channels for irrigation, power supply and drinking waters, conveyor channel in water treatment plants, storm waterways, some public fountains, culverts below roads and railways lines.

Open channel flows are observed in small-scale as well as large-scale situations. For example, the flow depth can be between few centimetres in water treatment plants and over 10 m in large

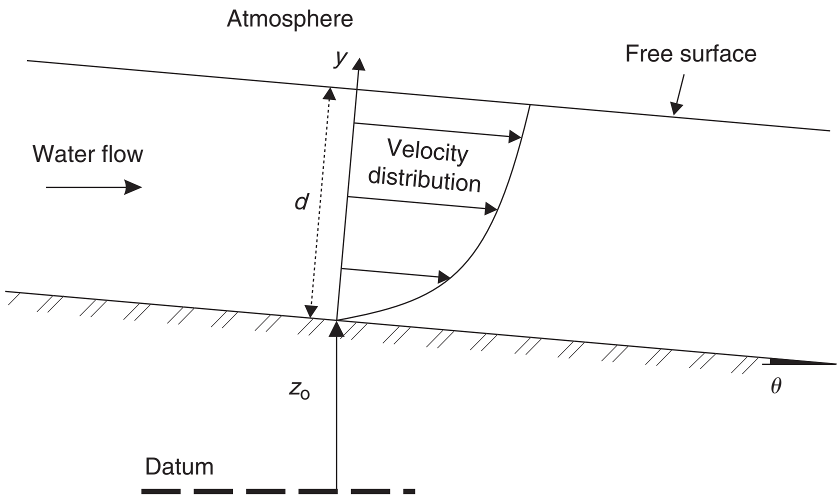

Fig. 1.2 Sketch of open channel flow.

Fig. 1.3 Wisconsin River and sand bars in Aug, 1966 (Courtesy of Dr Lou Maher) – looking upstream.

rivers. The mean flow velocity may range from less than 0.01 m/s in tranquil waters to above 50 m/s in high-head spillway. The range of total discharges[2] may extend from $Q \sim 0.001$ l/s in chemical plants to $Q > 10\,000\,m^3/s$ in large rivers or spillways. In each flow situation, however, the location of the free surface is unknown beforehand and it is determined by applying the continuity and momentum principles.

[2] In hydraulics of open channels, the water flow is assumed incompressible and the volume discharge is commonly used.

Table 1.1 Basic differences between pipe flow and open channel flow of an incompressible fluid

	Pipe flow	Open channel flow
Flow driven by	Pressure work	Gravity (i.e. potential energy)
Flow cross-section	Known (fixed by pipe geometry)	Unknown in advance because the flow depth is unknown beforehand
Characteristic flow parameters	Velocity deduced from continuity equation	Flow depth and velocity deduced by solving simultaneously the continuity and momentum equations
Specific boundary conditions		Atmospheric pressure at the flow free surface

1.4.3 Discussion

There are characteristic differences between open channel flow and pipe flow (Table 1.1). In an open channel, the flow is driven by gravity in most cases rather than by pressure work as with pipe flow. Another dominant feature of open channel flow is the presence of a free surface:

- the position of the free surface is unknown 'in advance',
- its location must be deduced by solving simultaneously the continuity and momentum equations, and
- the pressure at the free surface is atmospheric.

1.5 EXERCISES

Give the values (and units) of the specified fluid and physical properties:

(a) Density of water at atmospheric pressure and 20°C.
(b) Density of air at atmospheric pressure and 20°C.
(c) Dynamic viscosity of water at atmospheric pressure and 20°C.
(d) Kinematic viscosity of water at atmospheric pressure and 20°C.
(e) Kinematic viscosity of air at atmospheric pressure and 20°C.
(f) Surface tension of air and water at atmospheric pressure and 20°C.
(g) Acceleration of gravity in Brisbane.

What is the Newton's law of viscosity?

In a static fluid, express the pressure variation with depth.

Considering a spherical air bubble (diameter d_{ab}) submerged in water with hydrostatic pressure distribution:

(a) Will the bubble rise or drop?
(b) Is the pressure inside the bubble greater or smaller than the surrounding atmospheric pressure?
(c) What is the magnitude of the pressure difference (between inside and outside the bubble)?

Note: the last question requires some basic calculation.