UNIT OPERATIONS of CHEMICAL ENGINEERING

Vol. I

P. Chattopadhyay

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Unit Operations of Chemical Engineering

Vol. I

by

P. Chattopadhyay

B.Sc., AMIE (Chemical)
AMIE (Mechanical)
Senior Process Engineer
Formerly Part-time Lecturer of
Advance Course

KHANNA PUBLISHERS®
Investing in Learning®
Operational Office :
4575/15, Onkar House, Opp. Happy School,
Ground Floor, Daryaganj, New Delhi 110 002
Phones : 011-45033819 • *Mob.* 09811541460
email : contactus@khannapublishers.in

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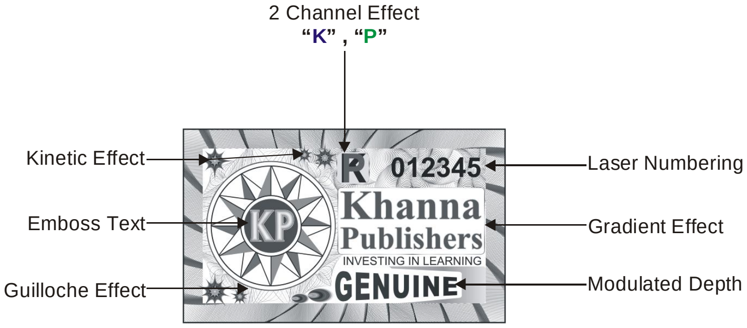

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PREFACE TO THIRD EDITION

True to my commitment in the preface to the 2nd edition plus to fulfil the popular demand of the students, I have mobilized great efforts to strengthen this volume "theoretically". And as an outcome of just that the book underwent the following revamps with the emphasis on design.

1. Much theoretical presentation of engineering importance has been injected into the chapter of Applied Hydraulics. Students will find such topics as : Pipe Sizing ; Two-K Method ; Full-Range for Flow Thru Pipes ; Measurement of Liq Flow in Open Channels ; Measurement of Slurry Pressure Drop ; Measurement of Gasflow thru Valves etc. quite interesting because of their downright practical significance.

Besides, Rules-of-Thumb on Fluid Flow Problems will give them a very good practical guideline to improve design of fluid flow systems.

2. A new topic : Sizing Critical Flow Orifices thru charts have been injected into the chapter of Compressible Flow.

3. Practical guidelines of Cyclone Design in good details have been inducted into the chapter of Particulate Solids Flow and Hydromechanical Separations. One design example backed by Cardinal Rules for Sizing Cyclones is an added bonanza.

4. In the chapter of Classification to Design of Hydrocyclones thru Nomographs has been detailed. One design example plus Hydrocyclone Balances have been plugged in.

5. The students will find the newly introduced Shortcut Method for Sizing Gravity Settler backed up by a couple of Design Examples in the chapter of Sedimentation very useful for practical design purposes.

6. There has been a considerable addition to the chapter of Filtration. The 'addendum' includes : Filtration Type and Mechanism ; Flowrate-Pressure Drop Relationship ; Selecting the Right Filter Fabric ; Selecting the Right Pressure Filter ; Design of Batch Pressure Filter.

Besides, the Disposable Filters and their advantages and disadvantages have been detailed.

Special emphasis has been laid on latest filtration technology ; Clean-in-Place Filters. Construction and operation mechanism of such CIPs as Tubular Pressure Filters and DCF have been discussed in depth to give students a deep insight into such evolutionary systems.

7. The chapter of Mass Transfer Coefficients has been expanded to net in six numerical examples which are quite interesting and equally useful to grasp the mass transfer across the gas-liq, liq-liq and solid-liq boundaries.

8. Lastly, the Heat Transfer chapter has been greatly renovated to cover the details of Construction and Design of Shell-and-Tube Exchangers. Almost all the design parameters have been discussed at a length with relevant diagrams so that students are not left in the gaping.

Nevertheless forty numerical examples have been injected to its body to vitalize the theoretical exposition. And with that the book presents 545 solved numerical examples plus 112 additional problems.

In the process of making the script I have got remarkable assistance from renowned individual, publishers and manufacturing company who therefore deserve special acknowledgement which follows this preface.

Eventually the preface comes to conclusion with my hope that this enlarged and revamped edition will receive warm patronage from a wider cross-section of teachers and students of chemical engineering. Their suggestions and constructive criticism are always welcome with thanks.

P. Chattopadhyay

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1

Applied Hydraulics

1.1. FLUID

A fluid is a substance that undergoes continuous deformation when subjected to a shear stress.

Both gases and liquids are called fluids.

An ideal or perfect fluid is a hypothetical gas or liquid that offers no resistance to shear.

For Newtonian fluids the resistance to deformation is constant provided static pressure and temperature are fixed.

A fluid is called non-Newtonian fluid if the resistance offered by it to shear is a function of shear stress as well as temperature and pressure.

1.2. PRESSURE OF A FLUID

A system of compressive forces act upon a body of fluid in static equilibrium. The intensity of this force measured in terms of Newtons per square meter (*i.e.* Pascal) or, kilogram force per square meter (kgf/m^2) is called ***static pressure.***

$$1 \text{ Pascal} = 1 \text{ N/m}^2$$

Dynamic pressure is the difference between the impact pressure and static head.

Static head is the pressure in a fluid due to the head of fluid above the point concerned. For liquids (having constant density the static head P is given by

$$P = h.\rho.g. \text{ in N/m}^2$$

where h = head of liquid above the point, m ;

ρ = density of the liquid, kg/m^3 and $g = 9.81 \text{ m/s}^2$

A common type of pressure measuring device is the Bourdon pressure gage. It normally reads zero pressure when open to the atmosphere. The heart of the Bourdon pressure gage is a pressure sensing device built of a thin metal tube with an elliptical cross-section closed at one end which has been bent into an arc. The open end of the hollow tube is connected to the pressure source. As the pressure at the open end of the tube increases, the tube tends to straighten out. This tube movement is converted into a dial movement by a system of gears and levers.

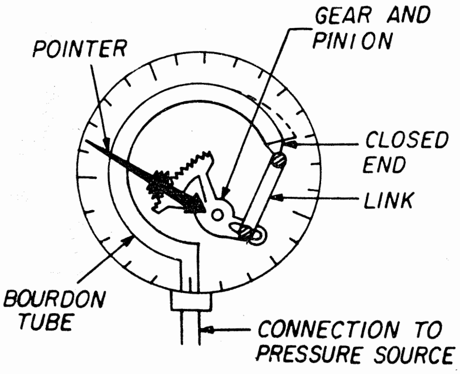

Fig. 1.1. Bourdon Pressure Gage.

Pressures, like temperature can be expressed by either absolute or relative scales. The relationship between relative and absolute pressure is given by the following expression :

$$\text{Gage pressure} + \text{Barometer pressure} = \text{Absolute pressure}$$

Absolute Pressure (mm Hg)	*Gage Pressure (mm Hg)*		*Gage Pressure (N/m^2)*	*Absolute Pressure (N/m^2)*
999	260	A Press. Above Atmospheric	0.34×10^5	1.333×10^5
760	21	Standard Pressure	0.028×10^5	1.0132×10^5
739	0	Barometric Pressure	0	0.985×10^5
612	127	A Press. Below Atmospheric	0.17×10^5	0.82×10^5
0	(– 739)	Perfect Vacuum	$-(0.985 \times 10^5)$	0

Absolute zero pressure defines the zero pressure condition of a system. This refers to an idealized state of a system void of all molecules so that a perfect vacuum exists and no pressure force is exerted on the chamber walls.

Absolute pressure is the pressure above absolute zero.

Atmospheric pressure is the pressure exerted by the atmosphere above absolute zero. It varies with location.

Standard atmospheric pressure is the pressure at sea level at 273 K. Its value is 101.325 kPa (760 mm Hg).

Note. One must not confuse the Standard Atmospheric Pressure with the Atmospheric Pressure. Actual atmospheric pressure is measured with a barometer and varies with altitude. Standard atmospheric pressure is a constant quantity and may not equal the barometric pressure. It is always used as reference in computing gas volume.

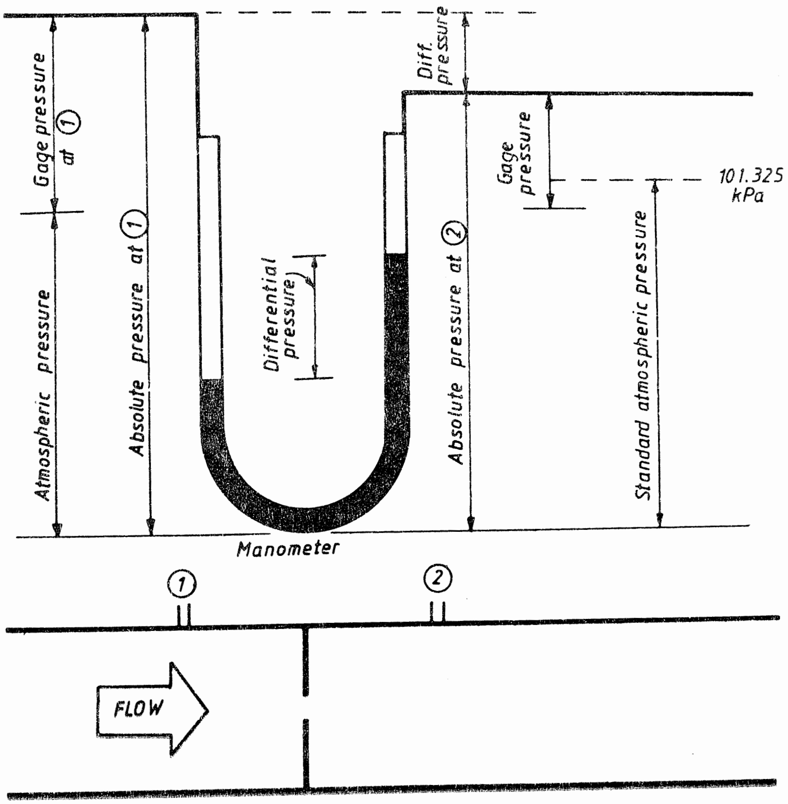

Fig. 1.2. Pressure levels.

1 Standard Atmosphere

760 mm Hg

14.696 pounds per square inch

10.33 m of water column

$101.325\ N/m^2$ (*i.e.* Pa)

Gage pressure is the pressure indicated by the pressure gage. It is the differential pressure between the pressure inside a pressure element and the surrounding atmospheric pressure.

Fig. 1.2 illustrates different pressure terms.

Vacuum is the pressure reading of a vacuum gage. It is always below atmospheric pressure.

Differentialpressure refers to pressure difference between two points. It is measured by either separating the two pressures with a diaphragm and measuring the force on the diaphragm or by observing the height of a liquid column in a manometer (see Fig. 1.2)

Static pressure is the actual pressure exerted by a fluid either at rest or in motion.

Static pressure is measured by means of either a piezometer ring or by drilling a small radial hole in a pipewall (Fig. 1.3). And that hole must be drilled perpendicular to the pipe, with no burrs or round corners.

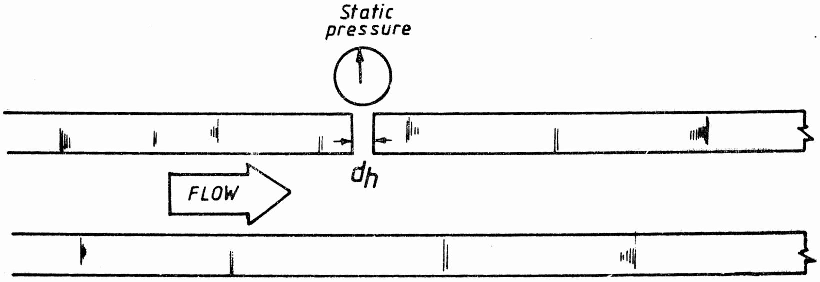

Fig. 1.3. Static pressure.

However, an error called bias error to the extent of – 0.5% to +1.1% of the static pressure creeps in if there is departure from recommended hole size, inclination, or edge condition (Fig. 1.4).

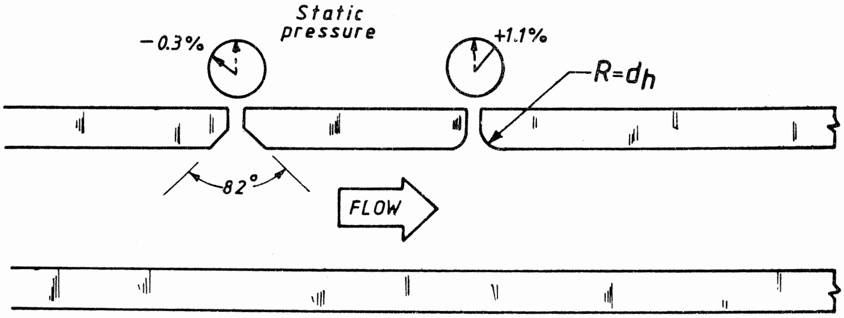

Fig. 1.4. Bias errors are the outcome of edge condition of wall-pressure taphole.

Dynamic Pressure. If a pressure taptube is bent perpendicular to the flow (Fig. 1.5), the static pressure gets increased by the directed kinetic energy of the flowing stream. When the stream velocity is zero, the pressure reading corresponds to the static pressure. But as the velocity increases, the difference is observed to increase by the square of the velocity. This difference in pressure levels is the measure of ***Dynamic Pressure*** at that point.

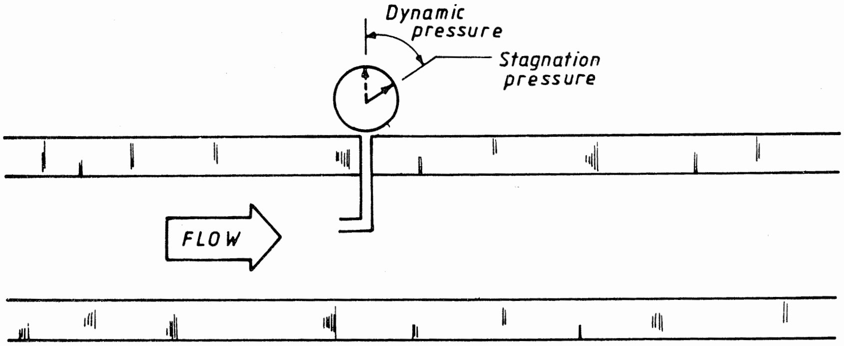

Fig. 1.5. Dynamic pressure is the difference between stagnation pressure and static pressure.

Total pressure is the sum of static pressure and dynamic pressure. It is also called ***Stagnation Pressure*** which may be read off with a pressure gage connected to a pitot tube (Fig. 1.5).

PRESSURE RELATIONS :

Flowline pressure $P_f = P_g + P_{bar}$ where P_f is the flowline pressure, kPa.absolute

P_g is the gage pressure, kPa

P_{bar} is the barometric pressure, kPa

Total pressure $P_t = P_f + P_d$

where P_t is the total pressure, kPa

P_d is the dynamic pressure, kPa

Dynamic pressure $P_d = \frac{1}{2} \cdot v_p^2 \cdot \rho$

where v_p is the point velocity along pipe radius, m/s

ρ is fluid density, kg/m^3

Differential pressure $\Delta P = P_{f,1} - P_{f,2}$

For the sake of simplicity, $\Delta P = P_1 - P_2$

1.3. PRESSURE OF A LIQUID COLUMN

The pressure (P) of column of liquid height h is

$$P = h.\rho.g., \quad \text{N/m}^2 \text{ (or Pa)} \qquad ...(1.1)$$

where ρ = density of liquid, kg/m^3 ; $g = 9.81$ m/s^2 ; h = height of liquid column, m

$$1 \text{ atm} = 760 \text{ mm Hg} = h.\rho.g = 0.76 \text{ (m)} \times 13590 \text{ (kg/m}^3) \times 9.81 \text{ (m/s}^2)$$
$$= 101\,325 \text{ N/m}^2 = 1.013 \times 10^5 \text{ N/m}^2 \text{ (}i.e.\text{ Pa)}$$
$$= 1.033 \times 10^4 \text{ mm H}_2\text{O} = 1.033 \times 10^4 \text{ kgf/m}^2 = 1.033 \text{ kgf/cm}^2$$

1 at (technical atmosphere)

$$= 1 \text{ kgf/cm}^2 = 10^4 \text{ kgf/m}^2 = 9.81 \times 10^4 \text{ N/m}^2$$
$$= 735 \text{ mm Hg} = 10^4 \text{ mm H}_2\text{O}$$

1.4. FUNDAMENTAL EQUATION OF HYDROSTATICS

$$\Delta P = h.\rho.g \text{ N/m}^2 \qquad ...(1.2)$$

where $\Delta P = P - P_0$

P_0 = pressure at the surface of the liquid, N/m^2

P = pressure of the liquid at a depth h (in m) from the surface of the liquid, N/m^2.

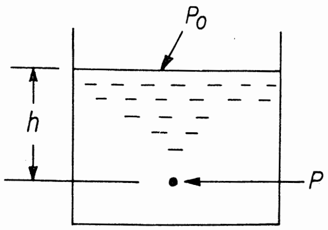

Fig. 1.6. Pressure of a liquid at any depth is proportional to the depth from the surface of the liquid.

1.5. VISCOSITY

Viscosity is the measure of a fluid's internal, or intermolecular, resistance to shear stress.

1.5.1. Absolute Viscosity. All fluids offer resistance to deformation when subjected to shear stress. Shown in Fig. 1.7 are two parallel plates of equal area, separated by a small distance ΔY, with a fluid in-between. A constant force, F, is applied to the top plate whereupon the plate plus the adjacent fluid move at constant velocity in the direction of force. However, the velocity attenuates with the depth of the fluid and it becomes zero at the bottom plate which is stationary.

Because of the consistency of the fluid, the shear stress is proportional to shear rate :

Shear Stress ∝ Shear Rate

Now shear stress is applied force upon area (F/A) and shear rate is $\Delta v/\Delta Y$, therefore

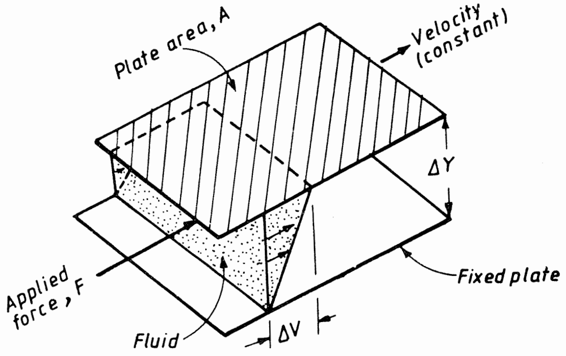

Fig. 1.7. Deformation of a fluid by an external force, F, generates a shear resistance within the body of the fluid.

$$\frac{F}{A} \propto \frac{\Delta v}{\Delta Y} \qquad \text{or,} \qquad \frac{F}{A} = \mu \cdot \frac{\Delta v}{\Delta Y} \qquad \ldots(1.3)$$

where μ = proportionality constant and is the fluid's ***Absolute Viscosity***, Pa.s

A = plate area, m^2 $\qquad$ Δv = velocity difference between two parallel plates, m/s

ΔY = spacing between parallel plates, m

For Newtonian fluids the relationship between shear stress and deformation rate is linear whereupon the absolute viscosity is constant. And there are other fluids ______fluids that are non-Newtonian (See Example 1.81) for which the viscosities are not constant (Fig. 1.8).

$$\textbf{Unit : } \mu = \frac{F}{A} \cdot \frac{\Delta Y}{\Delta v} = \frac{N}{m^2} \cdot \frac{m}{m/s} = \text{Pa. s}$$

$$= \frac{kg \cdot m/s^2}{m^2} = kg/m.\ s$$

1.5.2. Kinematic Viscosity. Mass is eliminated from the viscosity unit if the absolute viscosity is divided by the fluid density. The result is ***Kinematic Viscosity***, ν.

$$\nu = \frac{\mu}{\rho} = \frac{kg/m.\ s}{kg/m^3} = m^2/s \qquad \ldots(1.4)$$

Note. A commonly encountered viscosity unit is ***Poise*** which is

$$\mu = \frac{g}{cm.\ s}$$

Poise divided by grams per cubic centimeter gives the kinematic viscosity in ***Stokes***.

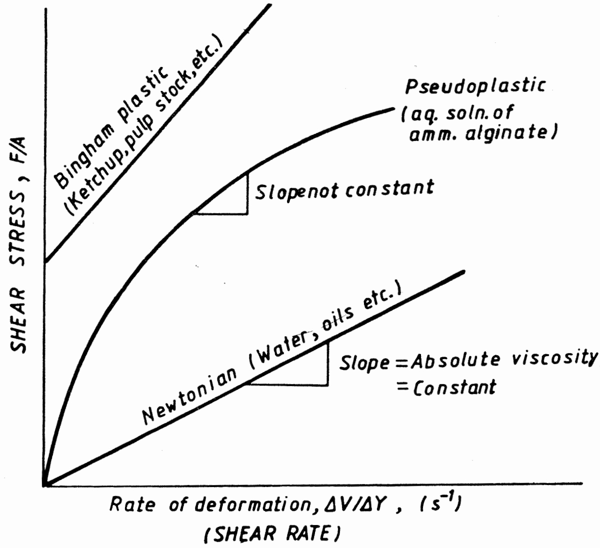

Fig. 1.8. Shear Stress vs. Shear Strain rate for Newtonian and Non-Newtonian fluids.

$$\nu = \frac{\mu}{\rho} = \frac{\text{g/cm. s}}{\text{g/cm}^3} = \text{cm}^2/\text{s}$$

1.6. FLOWRATE

The volumetric flowrate (Q_v) of a fluid (liquid or gas) is given by

$$Q_v = v.A, \text{ m}^3/\text{s} \qquad \text{...(1.5)}$$

where v = average velocity of flow, m/s and A = cross-sectional area of flow, m^2

The mass flowrate (Q_m) of fluid is given by

$$Q_m = Q_v \cdot \rho = v \cdot A \cdot \rho, \text{ kg/s}$$

where ρ = density of the fluid, kg/m^3

For flow through a round pipe,

$$Q_v = v \cdot \pi\, d^2/4 = 0.785\, v.d^2 \qquad \text{...(1.7)}$$

where d = internal diameter of the pipe, *m*

Volumetric flowrate and mean velocity of flow being known, pipe dia (ID) can be computed from the equation

$$d = \sqrt{Q_v/(0.785 v)}\ m = 1.128\sqrt{Q_v/v}\ m. \qquad \text{...(1.8)}$$

1.7. FLOW THROUGH PIPES AND CHANNELS

[A] **Reynolds Number (Re)** is a measure of forces of inertia and internal friction in a fluid flow. It is given by

$$\text{Re} = \frac{d \cdot v \cdot \rho}{\mu} = d \cdot \frac{v}{\nu} \qquad \text{... (1.9)}$$

where d = mean dia (ID) of pipe, m ; v = mean velocity of flow, m/s

ρ = density of liquid, kg/m^3; μ = dynamic viscosity of the fluid, Pa.s (*i.e.* kg/m.s)

ν = kinematic viscosity of the fluid, $\text{m}^2/\text{s}. = \mu/\rho$

Reynolds number characterizes the hydrodynamic conditions of flow.

Type of Flow	*Reynolds Number*
Laminar	$\text{Re} < 2300$
Transitional	$2300 < \text{Re} < 10^4$
Turbulent	$\text{Re} > 10^4$

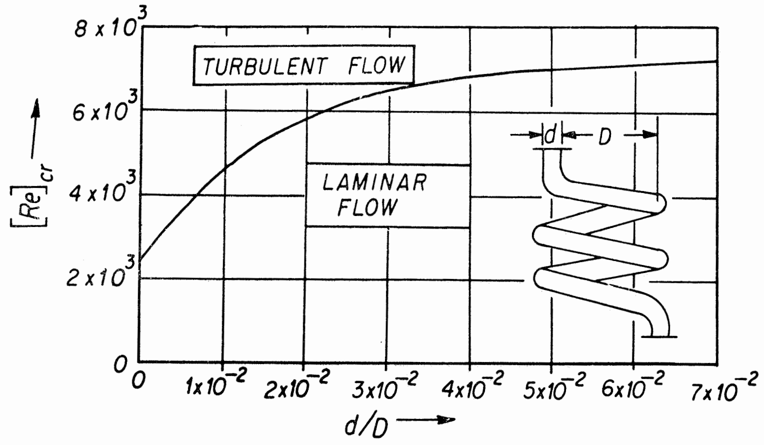

Fig. 1.9. Dependence of critical Reynolds number in coils on the ratio of tube dia to coil dia.

For flows through coils, a critical value of the Reynolds number [Re_{cr}] is introduced. It varies with the ratio *d/D* (Fig. 1.9).

d = diameter (ID) of the coil pipe, m
D = coil dia *i.e.* diameter of the coil turns, m

For flow through pipes that are not round

$$\mathrm{Re} = d_{eq} \cdot v \cdot \rho/\mu \qquad \text{... (1.10)}$$

where d_{eq} = equivalent diameter of the pipes, m
$\equiv 4 \times$ Hydraulic radius

Hydraulic radius (r_h) is the ratio of cross-sectional area of flow (A) to the wetted perimeter (Pm)

$$r_h = A/Pm \qquad \text{...(1.11)}$$

For a circular pipe of circular cross-section and completely filled with a liquid

$$r_h = \frac{\pi\, d^2}{4\, \pi\, d} = d/4 \qquad \text{...(1.12)}$$

Therefore, equivalent diameter of the pipe whose cross-section is not round

$$d_{eq} = 4 \cdot r_h = 4 \cdot A/Pm \qquad \text{... (1.13)}$$

[*B*] **Froude Number** (***Fr***) is the measure of the ratio of the force of inertia and the force of gravity

$$Fr = \frac{v^2}{g \cdot d} \qquad \text{...(1.14)}$$

[*C*] **Euler Number** (***Eu***) is the measure of the ratio of the pressure force to inertia force

$$Eu = \frac{\Delta P}{\rho \cdot v^2} \qquad \text{...(1.15)}$$

where, ΔP = the pressure loss, in N/m^2, in overcoming the hydraulic resistance.

1.8. FLUID FLOW SYSTEMS : ENERGY BALANCE

If a fluid flows past a solid boundary, momentum is transferred from the fluid to the boundary as a result of which there occurs a loss of system pressure.

The pressure loss of a fluid flowing through a pipe is a function of its velocity of flow, which can be calculated by applying a material balance on the process. Likewise, the power required to deliver a fluid through a complex network of piping system can be calculated by harnessing both material and energy balances.

[*a*] **The Material Balance.** The material balance is the schematic representation of the law of conservation of mass which states that the total mass of all substances taking part in process remains constant

Mass input = Mass output + Mass accumulation

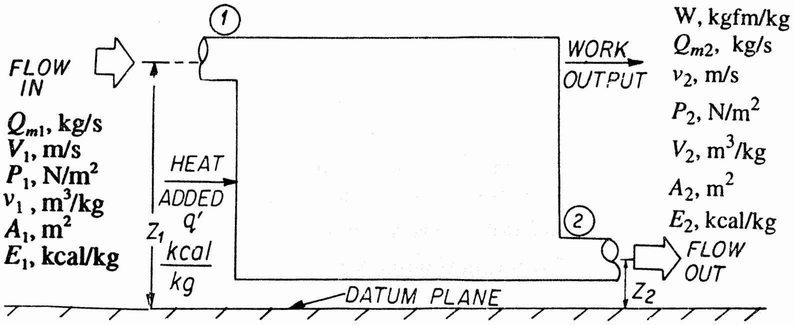

Fig. 1.10. Process flow system.

At steady state, the mass accumulation is nil and accordingly the mass flowrate into the system = mass flowrate out of the system

i.e. $$Q_{m_1} = Q_{m_2}$$

or, $$\frac{v_1 A_1}{V_1} = \frac{v_2 A_2}{V_2}$$

or, $$G_1 A_1 = G_2 A_2 \qquad \text{... (1.16)}$$

where Q_m = mass flowrate, kg/s ; v = average velocity of flow, m/s

A = cross-section of flow area, m^2 and V = specific volume of the fluid, m^3/kg

[*b*] **The Energy Balance.** The total energy entering a system must equal the total energy leaving the system. This is the law of conservation of energy and is the very basis of **Energy Balance.**

The energies to be considered can be grouped under into two broad heads :

— the energy carried by the fluid

— the energy transferred between the system and the surroundings.

[*I*] **The energy carried by the fluid includes** :

1. **Internal Energy (E).** This is the energy contributed by the chaotic motion of the molecules with which the system is composed of. This is an intrinsic property of the fluid.

2. **Potential Energy ($Z.g/g_c$).** This is the energy due to the position of the fluid with respect to an arbitrary datum plane

$$g = 9.81 \text{ m/s}^2 \quad ; \quad g_c = 1 \frac{\text{kg.m}}{\text{s}^2 \cdot \text{N}}$$

3. **Kinetic Energy ($v^2/2g_c$).** It is the energy possessed by the fluid by virtue of its motion.

In some texts kinetic energy correction factor (α) has been introduced whereupon the K.E. term becomes $v^2/(2g_c\,\alpha)$. The kinetic energy correction factor (α) must be determined from the Fig. 1.11.

For fully developed turbulent flow, $\alpha \to 1$. For laminar flow α is less than unity and hence to be incorporated in the kinetic energy term.

[Since the contribution of K.E. to the total energy balance in fluid flow is small, α has been dropped for practical purposes.]

4. **Pressure Energy (PV).** It is the energy possessed by the fluid by being pushed into the system by the surroundings. So this is equal to the work-done by the surroundings

i.e. $$\text{Pressure energy} = \begin{bmatrix} \text{Force exerted by the fluid} \\ \text{immediately behind the} \\ \text{entrance point} \end{bmatrix} \times \begin{bmatrix} \text{The distance} \\ \text{through which} \\ \text{this force acts} \end{bmatrix} = [P.A] \times V/A = PV$$

[II] The energy transferred between the system and the surroundings includes.

1. **Heat Absorbed** (*q*) : by the fluid from the surroundings. The heat absorption may be an isothermal or non-isothermal process. This is exclusive of heat generated by friction.

2. **Work-done on the Surroundings** (*W*) : by the fluid flowing through the system. This is sometimes referred to as shaft work as the fluid is required to drive the turbine shaft or a reciprocating shaft or some other work producing apparatus connected from the system to the surroundings.

W is taken to be positive by convention if work is done by the fluid and transferred to the surroundings.

Hence the overall energy balance for unit mass for the process flow system as depicted in Fig. 1.10 can be represented as

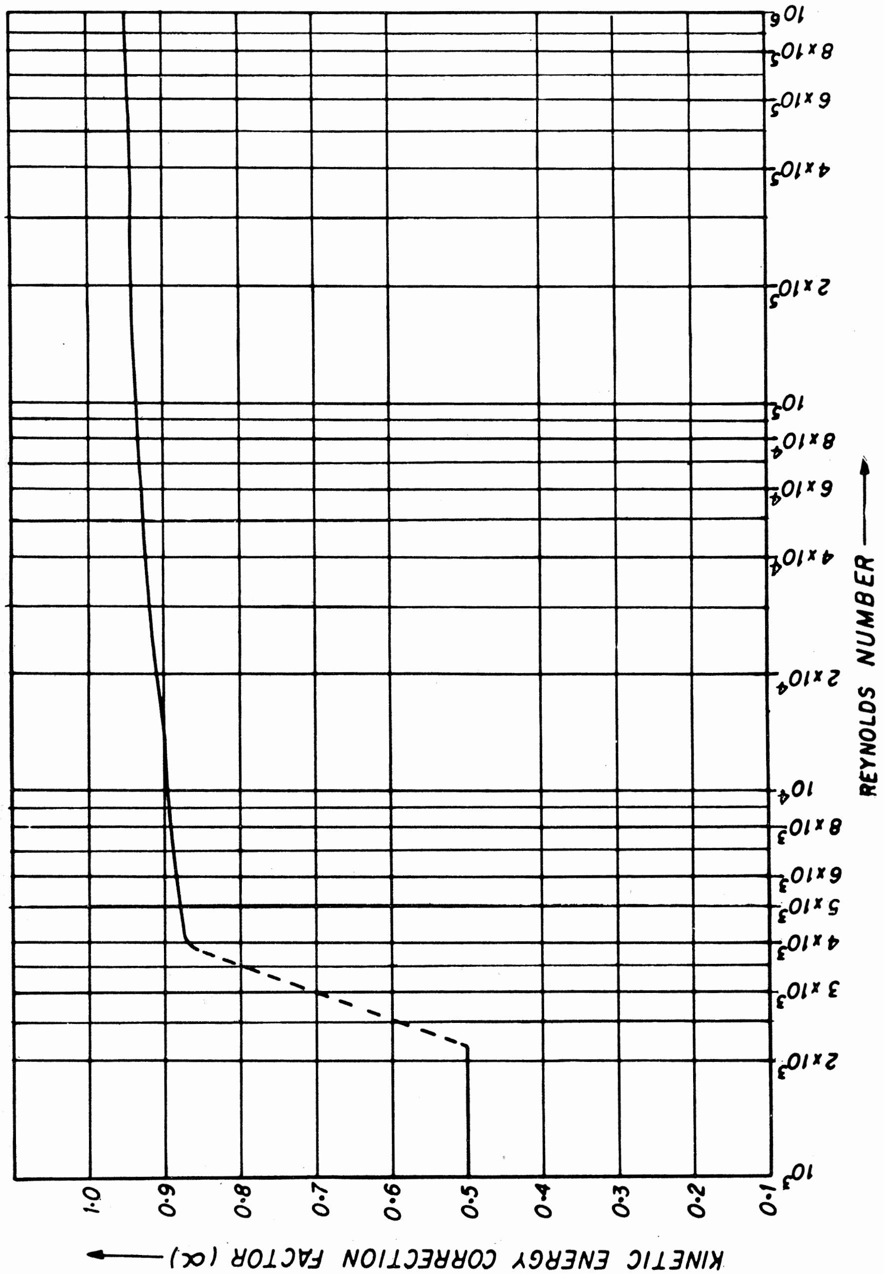

Fig. 1.11. Kinetic energy correction factor as a function of Reynolds number.

$$\underbrace{E_1 + Z_1 \cdot g/g_c + v_1^2/2\,g_c + P_1\,V_1 + q}_{\text{Energy transferred to the system}} = \underbrace{E_2 + Z_2 \cdot g/g_c + v_2^2/2g_c + P_2\,V_2 + W}_{\text{Energy transferred from the system to the surroundings}} \quad ...(1.17)$$

E as well as *PV* terms are the intrinsic property of the system. They can be summed up to a single quantity called enthalpy (*H*)

$$H = E + PV$$

Hence the above total energy balance equation simplifies to

$$H_1 + v_1^2/2\,g_c + Z_1 \cdot g/g_c + q = H_2 + v_2^2/2\,g_c + Z_2 \cdot g/g_c + W \quad ...(1.18)$$

or, $$(H_2 - H_1) + \frac{v_2^2 - v_1^2}{2.g_c} + \frac{(Z_2 - Z_1)\,g}{g_c} = q - W$$

or, $$\Delta H + \frac{\Delta v^2}{2.g_c} + \frac{g\,\Delta Z}{g_c} = q - W \qquad ...(1.19)$$

where Δ represents the change in going from state (**1**) to state (**2**).

[*C*] **Bernoulli Equation**

For an ideal fluid, viscosity is zero. Therefore, the momentum transport to the wall is zero. If the fluid is in isothermal flow and no heat is added to the system (*i.e.* $q = 0$) and no external work is done by the fluid upon the surrounding (*i.e.* $W = 0$), the foregoing energy-balance equation (1.17) reduces to

$$P_1 V_1 + Z_1 (g/g_c) + v_1^2/2g_c = P_2 V_2 + Z_2 (g/g_c) + v_2^2/2\,g_c \qquad ...(1.20)$$

as the internal energy of the fluid remains unchanged.

This is called Bernoulli equation that relates the pressure energy, potential energy and kinetic energy of a perfect fluid. Adopted to SI units, this further simplifies to

$$P_1 V_1 + Z_1\,g + v_1^2/2 = P_2 V_2 + Z_2 \cdot g + v_2^2/2 \qquad ...(1.21)$$

Each term of this equation has dimensions of energy per unit mass of fluid flowing. [Please see Appendix to the chapter of APPLIED HYDRAULICS]

(I) For Incompressible Fluid and Isothermal Flow

The density (ρ) of the fluid remains constant whereupon equation (1.21) becomes

$$\frac{P_1}{\rho} + Z_1 \cdot g + \frac{v_1^2}{2} = \frac{P_2}{\rho} + Z_2 {\cdot} g + \frac{v_2^2}{2} \qquad ...(1.22)$$

[*cf.* $V_1 = V_2 = 1/\rho$]

or, $$\frac{P_1 - P_2}{\rho \cdot g} + (Z_1 - Z_2) + \frac{v_1^2 - v_2^2}{2.g} = 0 \qquad ...(1.23)$$

or, $$\frac{\Delta P}{\rho \cdot g} + \Delta Z + \frac{\Delta v^2}{2 \cdot g} = 0 \qquad ...(1.24)$$

where $\Delta P = P_1 - P_2$; $\Delta Z = Z_1 - Z_2$ and $\Delta v^2 = v_1^2 - v_2^2$

All the terms in equations (1.23) and (1.24) have the dimension of head of the fluid.

(*a*) **FOR IDEAL (NON-VISCOUS) INCOMPRESSIBLE LIQUID**

$$Z_1 + \frac{P_1}{\rho \cdot g} + \frac{v_1^2}{2 \cdot g} = Z_2 + \frac{P_2}{\rho \cdot g} + \frac{v_2^2}{2 \cdot g} \qquad ...(1.25)$$

(*b*) **FOR REAL (VISCOUS) INCOMPRESSIBLE LIQUID**

$$Z_1 + \frac{P_1}{\rho \cdot g} + \frac{v_1^2}{2 \cdot g} - h_L = Z_2 + \frac{P_2}{\rho \cdot g} + \frac{v_2^2}{2 \cdot g} \qquad ...(1.26)$$

where Z = position head, m ; $v^2/2{\cdot}g$ = velocity head, m
$P/\rho{\cdot}g$ = static head, m and h_L = hydraulic loss head, m

(II) For Compressible Fluid and Isothermal Flow

The density (ρ) of the fluid no longer remains constant. Hence Bernoulli's equation for compressible fluid in isothermal flow becomes

$$\frac{P_1}{\rho_1 \cdot g} \ln P_1 + Z_1 + \frac{v_1^2}{2 \cdot g} = \frac{P_2}{\rho_2 \cdot g} \ln P_2 + Z_2 + \frac{v_2^2}{2 \cdot g} \qquad ...(1.27)$$

UNIT OPERATIONS of CHEMICAL ENGINEERING

Vol. I

This Book is the outcome of author's long years of professional experience as Process Engineer as well as his decade-long experience as part-time lecturer taking classes on such subjects as Fluid Mechanics, Heat Transfer and Separation Technologies. The subject matter of each chapter has been discussed to the depth and details to cater to the needs of the students studying Chemical Engineering in B.E., IIT and AMIE (Chemical) courses. The material of each chapter is divided between text and numerical examples with a few problems set in between for the practice of the students. The purpose is to provide a means for teaching, either through formal course or through self-study, the fundamental principles and techniques of Unit Operations of Chemical Engineering.

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