NEAR EAST UNIVERSITY

Faculty of Engineering

Department of Mechanical Engineering

FLUID DYNAMICS OF FLOW IN PIPES

Graduation Project
ME - 400

Student: Rami ABDELRAHIM (20011157)

Supervisor: Assist.Prof.Dr.Guner OZMEN

Nicosia - 2002

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ACKNOWLEDGMENT

I would like to express my thanks to the Near East university staff of Mechanical Engineering Department.

I would like to thank the chairman of the mechanical engineering department Prof. Dr. Kasif ONARAN for his valuable advices.

I would like to thank Assist. Prof. Dr. Guner OZMEN for her supervision. Under her guidance, I successfully overcome many difficulties through out this research.

Special thanks to my advisor Mr. T.Al shanabela for his help.

I would like to thank my friends E. Anan and A. Alwahab for their help to me during my student life in Cyprus.

Finally I would like to thank my family, especially my parents. Without their endless support and love for me, I would never achieve my current position.

SUMMARY

Fluids are of great importance in the engineering field and engineers are of great concern of the fluid flow in pipes. The main aim of this project is to prepare a survey report about the fluid dynamics of flow in pipes. The first chapter is an introductory chapter that includes the historical development of fluid mechanics and the definition of fluid and their importance in engineering fields. Also it includes definitions of some basic expressions that are used throughout the research. The second chapter explains the fluid properties such as: viscosity, surface tension, and vapor pressure and their effects in fluid flow.

Third chapter describes and classifies fluid flows. Viscous and inviscid flows, laminar and turbulent flows, compressible and incompressible flow, internal and external flows are explained briefly.

Fourth chapter deals with internal incompressible flow. Some aspects of steady flow in pressure conduits are discussed. The general characteristics of pipe flow, laminar and turbulent flow, effect of viscosity, critical Reynolds number, entrance conditions, fully developed laminar and turbulent flow, and the transition from laminar to turbulent flow are discussed.

Fifth chapter explains the pressure and shear distribution, velocity profile, and the different kinds of losses observed during fluid flow in pipes. Some important figures and tables are shown in this chapter.

CHAPTER 1

INTRODUCTION TO FLUID MECHANICS

1.1 HISTORICAL DEVELOPMENT OF FLUID MECHANICS

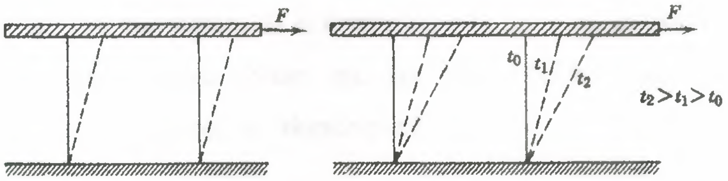
From time to time scientists discover more about the knowledge that ancient civilizations had about fluids, particularly in the areas of irrigation channels and sailing ships. The basic improvements for understanding the flow was not known until Leonardo da Vinci , who performed experiments, investigated, and speculated on waves and jets, eddies and streamlining, and even on flying. He contributed to the one dimensional equation for conservation of mass. Isaac Newton, by formulating his laws of motion and his law of viscosity, in addition to developing the calculus, paved the way for many great developments in fluid mechanics. Using Newton's laws of motion, numerous 18th century mathematicians solved many frictionless (zero-viscosity) flow problems. However, most flows are dominated by viscous effects, so engineers of the 17th and 18th centuries found the inviscid flow solutions unsuitable, and by experimentation they developed empirical equations, thus establishing the science of hydraulics.

Late in the 19th century the importance of dimensionless numbers and their relationship to turbulence was recognized, and dimensional analysis was born. In 1904 Ludwig Prandtl published a key paper, proposing that the flow fields of low-viscosity fluids be divided into two zones, namely a thin, viscosity-dominated boundary layer near solid surfaces, and an effectively inviscid outer zone away from the boundaries. This concept explained many former paradoxes, and enabled subsequent engineers to analyze far more complex flows.

1.2 DEFINITION OF A FLUID

Fluid mechanics deals with the behavior of fluids at rest and in motion. It is logical to begin with a definition of a fluid: a fluid is a substance that deforms continuously under the application of a shear (tangential) stress no matter how small the shear stress may be. Thus fluids comprise the liquid and gas (or vapor) phases of the physical forms in which matter exists. The distinction between a fluid and the solid state of matter is clear if you compare fluid and solid behavior. A solid deforms when a shear stress is applied, but its deformation does not continue to increase with time.

In Figure 1.1 the behavior of a solid and a fluid under the action of a constant shear force are contrasted. In Figure 1.la the shear force is applied to the solid through the upper of two plates to which the solid has been bonded. When the shear force is applied to the plate, the block is deformed as shown. From experiments in mechanics, it has known that the elastic limit of the solid material is not exceeded, the deformation is proportional to the applied shear stress, $\tau = F/A$, where A is the area of the surface in contact with the plate.



(a) (b)

Figure 1.1 Behavior of solid (a) and fluid (b), under the action of a constant shear.

To repeat the experiment with a fluid between the plates, use a dye marker to outline a fluid element as shown by the solid lines. When the force F, is applied to the upper plate, the fluid element continues to deform increasingly as long as the force is applied. The fluid in direct contact with the solid boundary has the same velocity as the boundary itself, there is no slip at the boundary. This is an experimental fact based on numerous observations of fluid behavior. The shape of the fluid element, at successive instants of time $t_o < t_1 < t_2$, is shown by the dashed lines, which represent the positions of the dye markers at successive times. Because the fluid motion continues under the application of a shear stress, then fluid may defined as a substance that cannot sustain a shear stress when at rest.

1.3 FIELDS OF FLUID MECHANICS

Knowledge and understanding of the basic principles and concepts of fluid mechanics are essential to analyze any system in which a fluid is the working medium. The design of virtually all means of transportation requires application of the principles of fluid mechanics. Included are aircraft for both subsonic and supersonic flight, ground effect machines, hovercraft, vertical takeoff and landing aircraft requiring minimum runway length, surface ships, submarines, and automobiles.

In recent years automobile manufacturers have given more consideration to aerodynamic design. This has been true for some time for the designers of both racing cars and boats. The design of propulsion systems for space flight as well as for toy rockets is based on the principles of fluid mechanics. The collapse of the Tacoma Narrows Bridge in 1940 is evidence of the possible consequences of neglecting the basic principles of fluid mechanics. It is commonplace today to perform model studies to determine the aerodynamic forces on, and flow fields around, buildings and structures. These include studies of skyscrapers, baseball stadiums, smokestacks, and shopping plazas.

The design of all types of fluid machinery including pumps, fans, blowers, compressors, and turbines clearly requires knowledge of the basic principles of fluid mechanics. Lubrication is an application of considerable importance in fluid mechanics. Heating and ventilating systems for private homes, large office buildings, and underground tunnels, and the design of pipeline systems are further examples of technical problem areas requiring knowledge of fluid mechanics. The circulatory system of the body is essentially a fluid system. It is not surprising that the design of blood substitutes, artificial hearts, heart-lung machines, breathing aids, and other such devices must rely on the basic principles of fluid mechanics.

The list of applications of the principles of fluid mechanics could be extended considerably. The main point here is that fluid mechanics is not a subject studied for purely academic interest, rather it is a subject with widespread importance both in our everyday experiences and in modem technology.

1.4 BASIC EQUATIONS USED IN FLUID MECHANICS

Analysis of any problem in fluid mechanics necessarily begins, either directly or indirectly, with statements of the basic laws governing the fluid motion. The basic laws, which are applicable to any fluid, are;

- The conservation of mass.
- Newton's second law of motion.
- The principle of angular momentum.
- The first law of thermodynamics.
- The second law of thermodynamics.

Clearly, not all basic laws always are required to solve any one problem. On the other hand, in many problems it is necessary to bring into the analysis additional relations, in the form of equations of state or constitutive equations that describe the behavior of physical properties of fluids under given conditions.

It is obvious that the basic laws with which we shall deal are the same as those used in mechanics and thermodynamics. The task here will be to formulate these laws in suitable forms to solve fluid flow problems and to apply them to a wide variety of problems. Such cases must resort to more complicated numerical solutions and results of experimental tests. Not all measurements can be made to the same degree of accuracy and not all data are equally good.

1.5 DIMENSIONS AND UNITS

Engineering problems are solved to answer specific questions. It goes without saying that the answer must include units. It makes a difference whether a pipe diameter required is 1 meter or 1 centimeter. Consequently, it is appropriate to present a brief review of dimensions and units.

Physical quantities such as length, time, mass, and temperature are referred as dimensions. In terms of a particular system of dimensions, all measurable quantities can be subdivided into two groups-primary quantities and secondary quantities. Primary quantities are those for which we set up arbitrary scales of measure, secondary quantities are those quantities whose dimensions are expressible in terms of the dimensions of the primary quantities. For example, the primary dimension of length may be measured in units of meters or centimeters. These units of length are related to each other through unit conversion factors.

Table 1.1 SI UNITS.

SI Units	Quantity	Unit	SI Symbol	Formula
SI base units:	Length	meter	m	-
	Mass	kilogram	kg	-
	Time	second	s	-
	Temperature	kelvin	k	-
SI supplementary unit:	Plane angle	radian	rad	-
SI derived units:	Energy	joule	J	N.m
	Force	newton	N	Kg.m/s^2
	Power	watt	W	J/s
	Pressure	pascal	Pa	N/m^2
	Work	joule	J	N.m

1.5.1 SYSTEMS OF DIMENSIONS

Any valid equation that relates physical quantities must be homogeneous, all terms in the equation must have the same dimensions. Newton's second law relates the four dimensions, F, M, L, and t. Thus force and mass cannot both be selected as primary dimensions without introducing a constant of proportionality that has dimensions and units. Length and time are primary dimensions in all dimensional systems in common use. In some systems, mass is taken as a primary dimension. In others, force is selected as a primary dimension. Thus there are three basic systems of dimensions as explained below, corresponding to the different ways of specifying the primary dimensions.

- Mass [M], length [L], time [t], temperature [T].
- Force [F], length [L], time [t], temperature [T].
- Force [F], mass [M], length [L], time [t], temperature [T].

Force [F] is a secondary dimension and the constant of proportionality in Newton's second law is dimensionless, mass [M] is a secondary dimension, and again the constant of proportionality in Newton's second law is dimensionless. Both force [F] and mass [M] have been selected as primary dimensions.

The numerical value of the constant of proportionality depends on the units of measure chosen for each of the primary quantities.

1.5.2 SYSTEM OF UNITS

As shown in Table 1.1, the unit of mass is the kilogram, the unit of length is the meter, the unit of time is the second, and the unit of temperature is the Kelvin. Force is a secondary dimension, and its unit is the Newton. In SI units, the constant of proportionality in Newton's second law is dimensionless and has a value of unity.

1.6 CONCLUSION

In this chapter topics were presented that are directly relevant to all subsequent chapters. A sketch of the historical development of fluid mechanics was given, the basis of fluid were defined before starting with the main chapters of this project. Also fluid was defined from a mechanics view point and set forth means of describing this substance and its actions in a quantitative manner using dimensions and units. The basic equations needed in studying fluid mechanics were presented. A table for SI units was given in this chapter that summarizes the units needed in fluid mechanics.

CHAPTER 2

PROPERTIES OF FLUIDS

2.1 INTRODUCTION

In this chapter fluid properties such as: viscosity, surface tension, vapor pressure, the conservation laws needed in the study of fluid mechanics and their relations to thermodynamic properties are discussed.

Viscosity is a measure of the resistance the fluid has to shear. It can be thought of as the internal stickiness of a fluid.

Surface tension is a property that results from the attractive forces between molecules. It manifests itself only in liquids at an interface.

Vapor pressure is the pressure resulting from molecules in the gaseous state. The vapor pressure is highly dependent on pressure and temperature, it increases significantly when the temperature increases.

2.2 GENERAL VIEW OF GASES AND LIQUIDS

Substances referred to as fluids may be liquids or gases. The definition of a liquid is: A state of matter in which the molecules are relatively free to change their positions with respect to each other but restricted by cohesive forces so as to maintain a relatively fixed volume. A gas is defined to be: A state of matter in which the molecules are practically unrestricted by cohesive forces. A gas has neither definite shape nor volume.

A force ΔF that acts on an area can be decomposed into a normal component ΔF_n and a tangential component ΔF_t. The force divided by the area upon which it acts is called a stress. The force vector divided by the area is a stress vector, the normal component of force divided by the area is a normal stress, and the tangential force divided by the area is a shear stress.

Mathematically, the shear stress τ is defined as;

$$\tau = \lim_{\Delta A \to 0} \frac{\Delta Ft}{\Delta A}$$

The fluids considered in this project are those liquids that move under the action of a shear stress, no matter how small that shear stress may be. This means that even a very small shear stress results in motion in the fluid. Gases obviously fall within this category of fluids. Some substances such as plastics may resist small shear stresses without moving.

It is worthwhile to consider the microscopic behavior of fluids in more detail. Consider the molecules of a gas in a container. These molecules are not stationary but move about in space with very high velocities. They collide with each other and strike the walls of the container in which they are confined, giving rise to the pressure exerted by the gas. If the volume of the container is increased while the temperature is maintained constant, the number of molecules impacting on a given area is decreased and as a result the pressure decreases. If the temperature of a gas in a given volume increases velocities, the pressure increases due to increased molecular activity.

Despite the high molecular attractive forces in a liquid, some of the molecules at the surface escape into the space above. If the liquid is contained, equilibrium is established between outgoing and incoming molecules. The presence of molecules above the liquid surface leads to a so-called vapor pressure. This pressure increases with temperature. For example, for water at 20°C this pressure is 0.02 times the atmospheric pressure.

2.3 VISCOSITY OF FLUIDS

Viscosity is a measure of the resistance the fluid has to shear. Viscosity can be thought of as the internal stickiness of a fluid. It is one of the properties that control the amount of fluid that can be transported in a pipeline during a specific period of time. It accounts for the energy losses associated with the transport of fluids in ducts, channels, and pipes. Further, viscosity plays a primary role in the generation of turbulence. Needless to say, viscosity is an extremely important fluid property in our study of fluid flows. The rate of deformation of a fluid is directly linked to the viscosity of the fluid.

For a given stress, a highly viscous fluid deforms at a slower rate than a fluid with a low viscosity.

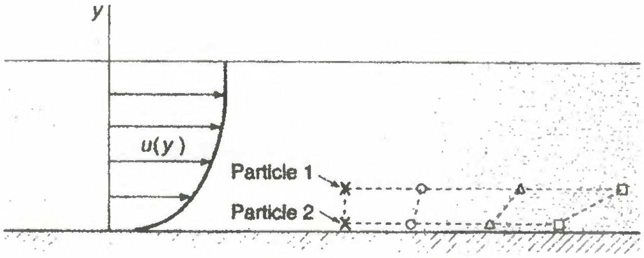


Figure 2.1 Relative movement of two fluid particles in the presence of shear stresses.

Consider a flow in which the fluid particles move in the x-direction at different speeds, so that particle velocities u varies with the y-coordinate. Figure 2.1 shows two particle positions at different times. For such a simple flow field, in which $u = u(y)$, the viscosity μ of the fluid can be defined by the relationship;

$$\tau = \mu \frac{du}{dy}$$

where;

τ : the shear stress

μ : the viscosity of fluid

u : the velocity in the x-direction

$\frac{du}{dy}$: the velocity gradient

The concept of viscosity and velocity gradients can also be illustrated by considering a fluid within the small gap between two concentric cylinders. A torque is necessary to rotate the inner cylinder at constant speed while the outer cylinder remains stationary. This resistance to the rotation of the cylinder is due to viscosity.

If the shear stress of a fluid is directly proportional to the velocity gradient, the fluid is said to be a Newtonian fluid. Fortunately, many common fluids, such as air, water, and oil, are Newtonian. Non-Newtonian fluids, with shear stress versus strain rate relationships as shown in Figure 2.2, often have a complex molecular composition.

Dilatants become more resistant to motion as the strain rate increases, and pseudoplastics become less resistant to motion with increased strain rate.

Ideal plastics require a minimum shear stress to cause motion. Clay suspensions and toothpaste are examples that also require a minimum shear to cause motion, but they do not have a linear stress-strain rate relationship.

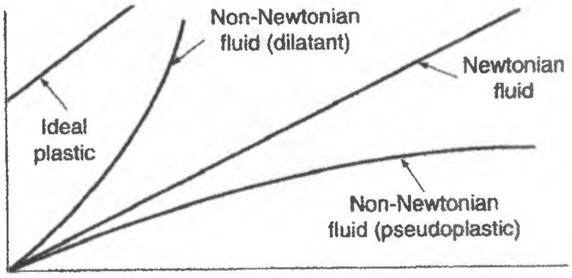


Figure 2.2 Newtonian and non-Newtonian fluids.

An important effect of viscosity is to cause the fluid to adhere to the surface, this is known as the no-slip condition. The viscosity is very dependent on temperature in liquids in which cohesive forces play a dominant role, note that the viscosity of liquids decreases with increased temperature, as shown in Figure 2.3. For a gas it is molecular collisions that provide the internal stresses, so that as the temperature increases, resulting in increased molecular activity, the viscosity increases. Note that the percentage change of viscosity in a liquid is much greater than in a gas for the same temperature difference.

2.4 SURFACE TENSION

Surface tension is a property that results from the attractive forces between molecules. As such, it manifests itself only in liquids at an interface, usually a liquid-gas interface. The forces between molecules in the bulk of a liquid are equal in all directions, and as a result, no net force is exerted on the molecules. However, at an interface the molecules exert a force that has a resultant in the interface layer. This force holds a drop of water suspended on a rod and limits the size of the drop that may be held. It also causes the small drops from a sprayer or atomizer to assume spherical shapes. It may also play a significant role when two immiscible liquids (e.g., oil and water) are in contact with each other.

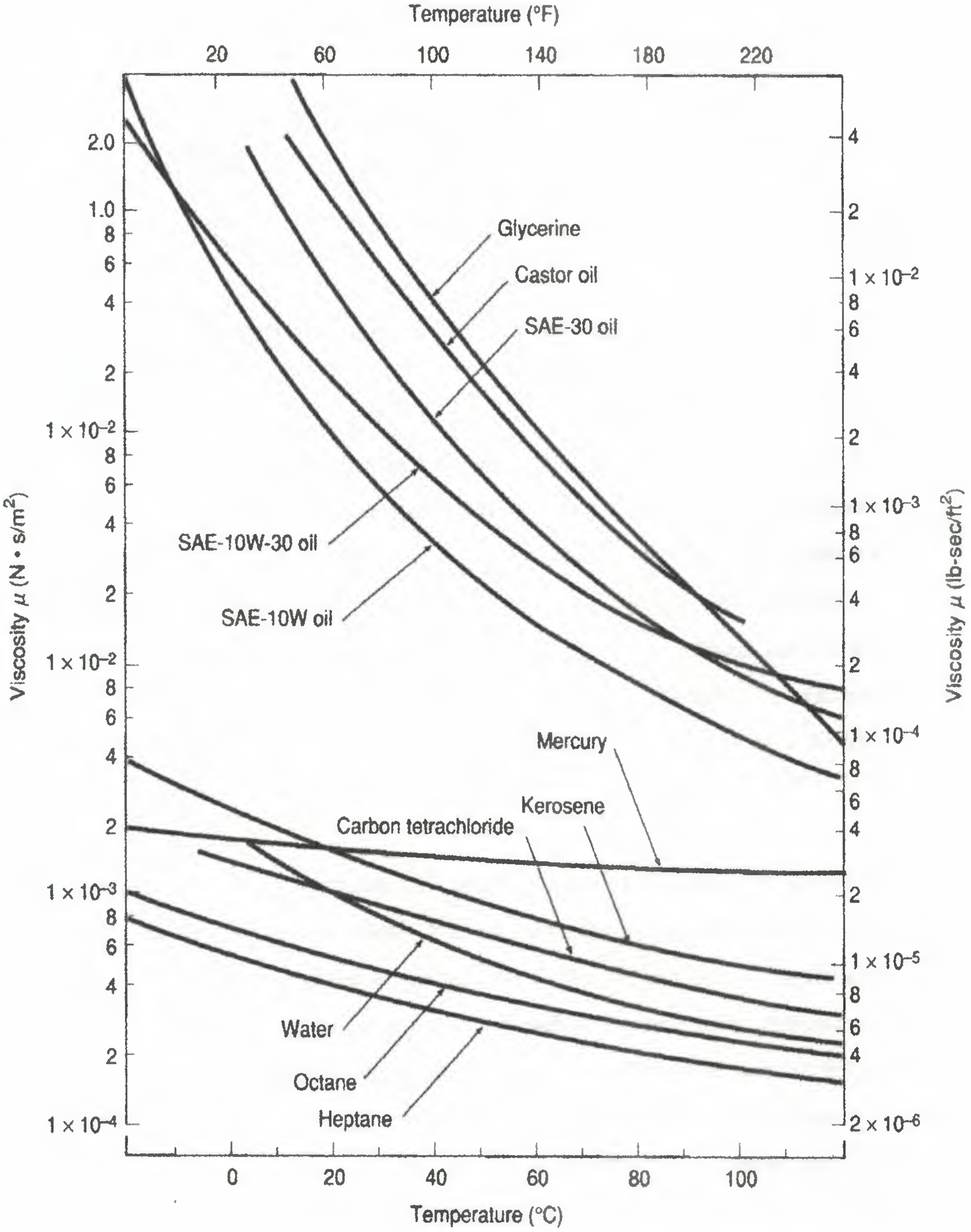
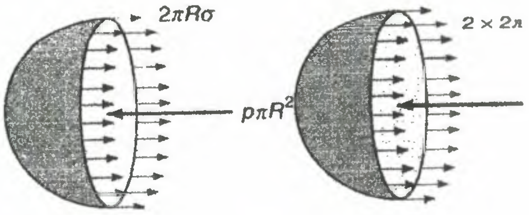


Figure 2.3 Viscosity versus temperature for several liquids.

Surface tension has units of force per unit length, N/m. The force due to surface tension results from a length multiplied by the surface tension; the length to use is the length of fluid in contact with a solid, or the circumference in the case of a bubble. A surface tension effect can be illustrated by considering the free-body diagrams of half a droplet and half a bubble as shown in Figure 2.4. The droplet has one surface and the bubble is composed of a thin film of liquid with an inside surface and an outside surface.



(a) (b)

Figure 2.4 Internal forces in a droplet (a) and a bubble (b).

2.5 VAPOR PRESSURE

When a small quantity of liquid is placed in a closed container, a certain fraction of the liquid will vaporize. Vaporization will terminate when equilibrium is reached between the liquid and gaseous states of the substance in the container, in other words, when the number of molecules escaping from the water surface is equal to the number of incoming molecules. The pressure resulting from molecules in the gaseous state is the vapor pressure. The vapor pressure is different from one liquid to another. For example, the vapor pressure of water at standard conditions (15°C, 101.3 kPa) is 1.70 kPa absolute and for ammonia it is 33.8 kPa absolute.

The vapor pressure is highly dependent on pressure and temperature, it increases significantly when the temperature increases. For example, the vapor pressure of water increases to 101.3 kPa if the temperature reaches 100°C. It is of course no coincidence that the water vapor pressure at 100°C is equal to the standard atmospheric pressure. At that temperature the water is boiling, that is the liquid state of the water can no longer be sustained because the attractive forces are not sufficient to contain the molecules in a liquid phase. In general, a transition from the liquid state to the gaseous state occurs if the local absolute pressure is less than the vapor pressure of the liquid.

In liquid flows, conditions can be created that lead to a pressure below the vapor pressure of the liquid. When this happens, bubbles are formed locally. This phenomenon called cavitation which can be very damaging when these bubbles are transported by the flow to higher pressure regions. What happens is that the bubbles collapse upon entering the higher pressure region, and this collapse produces local pressure spikes, which have the potential of damaging a pipe wall or a ship's propeller.

2.6 CONSERVATION LAWS

From experience it has been found that fundamental laws exist that appear exact, that is if experiments are conducted with the utmost precision and care, deviations from these laws are very small and in fact, the deviations would be even smaller if improved experimental techniques were employed.

A more specific law based on the conservation of momentum is Newton's second law which states that: The sum of all external forces acting on a system is equal to the time rate of change of linear momentum of the system. A parallel law exists for the moment of momentum: The rate of change of angular momentum is equal to the sum of all torques acting on the system.

Another fundamental law is the conservation of energy, which is also known as the first law of thermodynamics. If a system is in contact with the surroundings, its energy increases only if the energy of the surroundings experiences a corresponding decrease.

2.7 THERMODYNAMIC PROPERTIES AND RELATIONSHIPS

For incompressible fluids, the laws mentioned in the preceding section suffice. This is usually true for liquids but also for gases if insignificant pressure, density, and temperature changes occur. However, for a compressible fluid it may be necessary to introduce other relationships, so that density, temperature, and pressure changes are properly taken into account. An example is the prediction of changes in density, pressure, and temperature when compressed gas is released from a container. Thermodynamic properties, quantities that define the state of a system, either depend on the system's mass or are independent of the mass. The former is called an extensive property and the latter is called an intensive property. An intensive property can be obtained by dividing the extensive property by the mass of the system. Temperature and pressure are intensive properties while momentum and energy are extensive properties.

2.8 CONCLUSION

In this chapter a number of fundamental properties of fluids such as viscosity, surface tension, and vapor pressure were discussed. An understanding of these properties is essential if one is to apply basic principles of fluid mechanics to the solution of practical problems. The differences between Newtonian and non-Newtonian fluids were explained. The effects of attractive forces between molecules were also discussed. Many figures and equations were presented which are important in understanding the properties of fluids.

CHAPTER 3

CLASSIFICATION OF FLUID FLOWS

3.1 INTRODUCTION

In this chapter, a brief overview of different types of flows, such as viscous and inviscid flows, laminar and turbulent flows, incompressible and compressible flows, and internal and external flows are discussed. Although most of the notions presented here are redefined and discussed in detail, it will be helpful at this point to introduce the general classification of fluid flows. A fluid may be classified as either a viscous or inviscid flow. In a viscous flow the effects of viscosity are important and cannot be ignored. While in an inviscid flow the effect of viscosity can be neglected.

Classification of fluid flows separates flows into incompressible and compressible flows. An incompressible flow exists if the density of each fluid particle remains relatively constant.

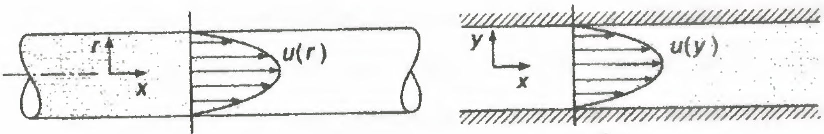
A viscous flow can be classified as either a laminar flow or a turbulent flow. In a laminar flow the fluid flows with no significant mixing of neighboring fluid particles. In a turbulent flow fluid motions vary irregularly so that quantities such as velocity and pressure show a random variation with time and space coordinates. The flow of fluids may be internal or external flow. Internal flow involves flow in a bounded region while external flow involves fluid in an unbounded region.

3.2 ONE, TWO, AND THREE DIMENSIONAL FLOWS

In the Eulerian description of motion the velocity vector, in general, depends on three space variables and time, that is, $V = V(x, y, z, t)$. Such a flow is a three-dimensional flow, because the velocity vector depends on three space coordinates. The solutions to problems in such a flow are very difficult and are beyond the scope of an introductory course. Even if the flow could be assumed to be steady, it would remain a three-dimensional flow.

Often a three-dimensional flow can be approximated as a two-dimensional flow. For example, the flow over a wide dam is three-dimensional because of the end conditions, but the flow in the central portion away from the ends can be treated as two dimensional. In general, a two-dimensional flow is a flow in which the velocity vector depends on only two space variables. An example is a plane flow, in which the velocity vector depends on two spatial coordinates, x and y, but not z. This flow is normal to a plane surface; the fluid decelerates and comes to rest at the stagnation point. The two velocity components, u and v, depend only on x and y, that is, $u = u(x, y)$ and $v = v(x, y)$ in a plane flow.

A one-dimensional flow is a flow in which the velocity vector depends on only one space variable. Such flows occur in long, straight pipes or between parallel plates. The velocity in the pipe varies only with r; u = u(r). The velocity between parallel plates varies only with the coordinate y; u = u (y). Even if the flow is unsteady so that $u = u(y, t)$, as would be the situation during startup, the flow is one dimensional.



(a) (b)

Figure 3.1 One-dimensional flow; (a) flow in a pipe, (b) flow between parallel plates.

The flows shown in Figure 3.1 may also be referred to as developed flows, that is the velocity profiles do not vary with respect to the space coordinate in the direction of flow.

There are many engineering problems in fluid mechanics in which a flow field is simplified to a uniform flow: the velocity, and other fluid properties are constant over the area. This simplification is made when the velocity is essentially constant over the area, a rather common occurrence. Examples of such flows are relatively high-speed flow in a pipe section, and flow in a stream. The average velocity may change from one section to another; the flow conditions depend only on the space variable in the flow direction. The schematic representation of the velocity is shown in Figure 3.2.

For large conduits, however, it may be necessary to consider hydrostatic variation in the pressure normal to the streamlines.

3.3 VISCOUS AND INVISCID FLOWS

A fluid flow may be broadly classified as either a viscous flow or an inviscid flow. An inviscid flow is one in which viscous effects do not significantly influence the flow and are thus neglected. In a viscous flow the effects of viscosity are important and cannot be ignored.

Figure 3.2 Uniform velocity profiles.

Based on experience, it has been found that the primary class of flows, which can be modeled as inviscid flows, is external flows, that is, flows that exist exterior to a body. Inviscid flows are of primary importance in flows around streamlined bodies, such as flow around an airfoil or a hydrofoil. Any viscous effects that may exist are confined to a thin layer, called a boundary layer, which is attached to the boundary, such as that shown in Figure 3.3. The velocity in a boundary layer is always zero at a fixed wall as a result of viscosity. For many flow situations, boundary layers are so thin that they can simply be ignored when studying the gross features of a flow around a streamlined body.

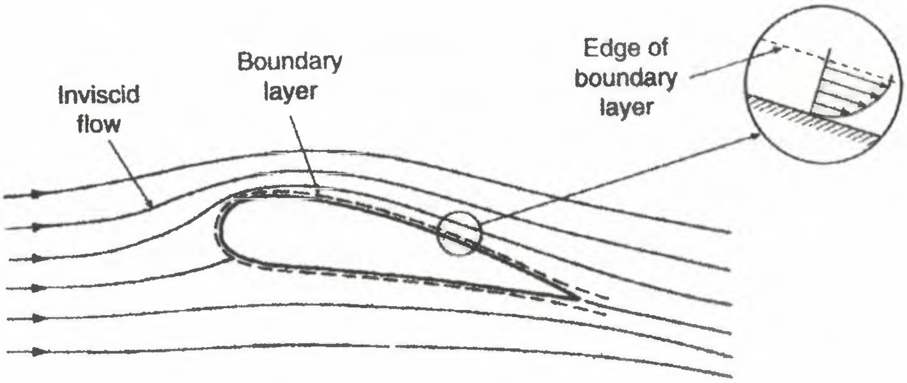
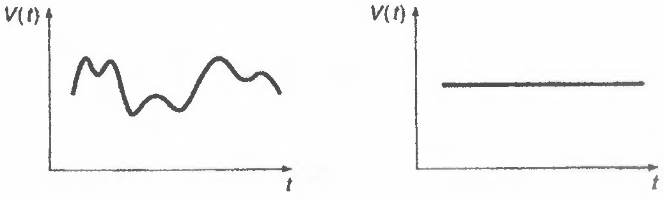


Figure 3.3 Flow around an airfoil.

Viscous flows include the broad class of internal flows, such as flows in pipes and conduits and in open channels. In such flows viscous effects cause substantial losses and account for the huge amounts of energy that must be used to transport oil and gas in pipelines. The no-slip condition resulting in zero velocity at the wall, and the resulting shear stresses, lead directly to these losses.

3.4 LAMINAR AND TURBULENT FLOWS

A viscous flow can be classified as either a laminar flow or a turbulent flow. In a laminar flow the fluid flows with no significant mixing of neighboring fluid particles. If dye were injected into the flow, it would not mix with the neighboring fluid except by molecular activity, it would retain its identity for a relatively long period of time. Viscous shear stresses always influence a laminar flow. The flow may be highly time dependent, as shown by the output of a velocity probe in Figure 3.4a, or it may be steady, as shown in Figure 3.4b.



(a) (b)

Figure 3.4 Velocity as a function of time in a laminar flow;
(a) unsteady flow, (b) steady flow.

In a turbulent flow fluid motions vary irregularly so that quantities such as velocity and pressure show a random variation with time and space coordinates. The physical quantities are often described by statistical averages. In this sense we can define a steady turbulent flow: a flow in which the time-average physical quantities do not change in time. Figure 3.5 shows the velocity measurements in an unsteady and a steady turbulent flow. A dye injected into a turbulent flow would mix immediately by the action of the randomly moving fluid particles, it would quickly lose its identity in this diffusion process.

The flow regime depends on three physical parameters describing the flow conditions. The first parameter is a length of the flow field, such as the thickness of a boundary layer or the diameter of a pipe. If this length is sufficiently large, a flow disturbance may increase and the flow may be turbulent. The second parameter is a velocity, for a large enough velocity the flow may be turbulent. The third parameter is the kinematic viscosity.

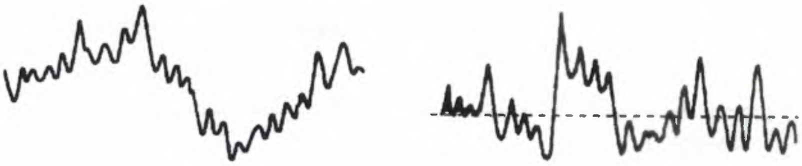


Figure 3.5 Velocity as a function of time in a turbulent flow.

The three parameters can be combined into a single parameter that can serve as a tool to predict the flow regime. This quantity is the Reynolds number R_e, a dimensionless parameter, defined as;

$$\mathrm{Re} = \frac{VD}{\nu}$$

Where;

D: the diameter of the pipe
V: the velocity
ν: the kinematic viscosity

If the Reynolds number is relatively small, the flow is laminar, if it is large then the flow is turbulent. This is more precisely stated by defining a critical Reynolds number, Re_{cr}, so that the flow is laminar if $\mathrm{Re} < \mathrm{Re}_{cr}$. For example, in a flow inside a rough walled pipe it is found that $\mathrm{Re}_{cr} \approx 2000$. This is the minimum critical Reynolds number and is used for most engineering applications. If the pipe wall is extremely smooth, the critical Reynolds number can be increased as the fluctuation level in the flow is decreased. The flow can also be intermittently turbulent and laminar, this is called an intermittent flow. This phenomenon can occur when the Reynolds number is close to Re_{cr}.

In a boundary layer that exists on a flat plate, due to a constant-velocity fluid stream, as shown in Figure 3.6, the length scale changes with distance from the upstream edge. A Reynolds number is calculated using the length x as the characteristic length. For a certain X_T, Re becomes Re_{cr} and the flow undergoes transition from laminar to turbulent. For a smooth plate in a uniform flow with a low free-stream fluctuation level, values as high as $Re_{cr} = 10^6$ have been observed. In most engineering applications engineers assume a rough wall, or high free-stream fluctuation level, with an associated critical Reynolds number of approximately 3×10^5.

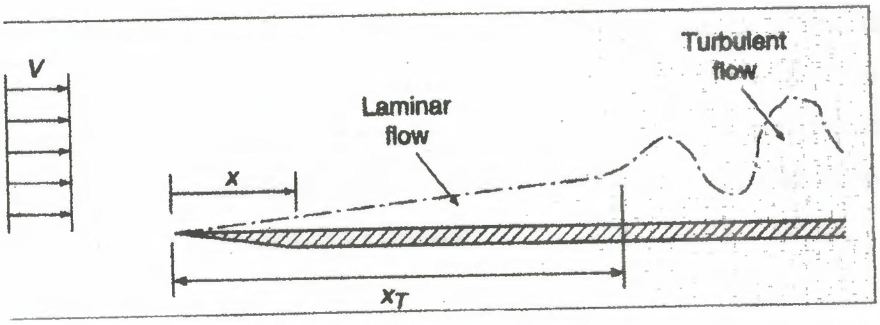


Figure 3.6 Boundary layer flow on a flat plate.

3.5 INCOMPRESSIBLE AND COMPRESSIBLE FLOWS

Classification of fluid flows in this chapter separates flows into incompressible and compressible flows. An incompressible flow exists if the density of each fluid particle remains relatively constant as it moves through the flow field. If the density is constant, then obviously, the flow is incompressible, but that would be a more restrictive condition.

Atmospheric flow, in which p = p(z), where z is vertical, and flows that involve adjacent layers of fresh and salt water, as happens when rivers enter the ocean, are examples of incompressible flows in which the density varies. In addition to liquid flows, low-speed gas flows, such as the atmospheric flow referred to above, are also considered to be incompressible flows.

Incompressible gas flows include atmospheric flows, the aerodynamics of landing and takeoff of commercial aircraft, heating and air-conditioning airflows, flow around automobiles and through radiators, and the flow of air around buildings. While Compressible flows include the aerodynamics of high-speed aircraft, airflow through jet engines, steam flow through the turbine in a power plant, airflow in a compressor, and the flow of the air-gas mixture in an internal combustion engine.

3.6 INTERNAL AND EXTERNAL FLOWS

Internal flow involves flow in a bounded region, as the name implies. External flow involves fluid in an unbounded region in which the focus of attention is on the flow pattern around a body immersed in the fluid.

The motion of a real fluid is influenced significantly by the presence of the boundary. Fluid particles at the wall remain at rest in contact with the wall. In the flow field a strong velocity gradient exists in the vicinity of the wall, a region referred to as the boundary layer. A retarding shear force is applied to the fluid at the wall the boundary layer being a region of significant shear stresses.

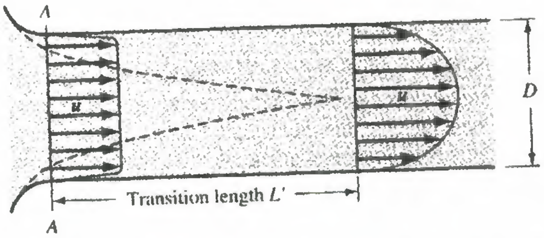


Figure 3.7 Fully developed velocity profile for internal flow.

In Figure 3.7 at section *A-A*, near a well-rounded entrance, the velocity profile is almost uniform over the cross section. The action of the wall shearing stress is to slow down the fluid near the wall. As a consequence of continuity, the velocity must increase in the central region. Beyond a transitional length L' the velocity profile is fixed since the boundary influence has extended to the pipe centerline. The transition length is a function of the Reynolds number thus;

$$\frac{L'}{D} = 0.058\text{Re}$$

In turbulent flow the boundary layer grows more rapidly and the transition length is considerably shorter than that of the laminar flow. In external flows, with an object in an unbounded fluid, the frictional effects are confined to the boundary layer next to the body. Examples include a golf ball in flight, a sediment particle, and a boat. The fully developed velocity profile shown in Figure 3.7 for an internal flow is unlikely to exist in external flows.

3.7 ENTRANCE FLOW AND DEVELOPED FLOW

A developed flow results when the velocity profile ceases to change in the flow direction. In the laminar flow entrance region the velocity profile changes in the flow direction as shown in Figure 3.8.

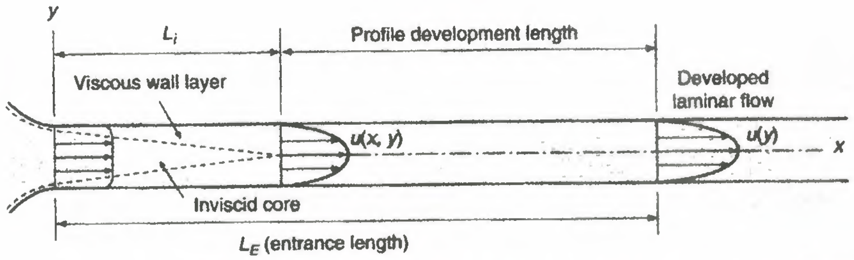


Figure 3.8 Laminar entrance flow in a pipe or a wide rectangular channel.

The idealized flow from a reservoir begins at the inlet as a uniform flow, the viscous wall layer then grows over the inviscid core length L. Until the viscous stresses dominate the entire cross section, the profile then continues to change in the profile development region due to viscous effects until a developed flow is achieved. The inviscid core length is one-fourth to one-third of the entrance length L_E depending on the conduit geometry, shape of the inlet, and the Reynolds number. For a laminar flow in a circular pipe with a uniform profile at the inlet, the entrance length is given by;

$$\frac{L_E}{D} = 0.065\mathrm{R_e}$$

Flow in a pipe has been observed at Reynolds numbers in excess of 40.000 for carefully controlled conditions. However, for engineering applications a value of about 2000 is the highest Reynolds number for which laminar flow is assured; this is due to vibrations of the pipe, fluctuations in the flow, or roughness elements on the pipe wall.

For a laminar flow in a high-aspect-ratio channel with a uniform profile at the inlet, the entrance length is;

$$\frac{L_E}{h} = 0.04\mathrm{R_e}$$

Where the Reynolds number is based on the average velocity and the distance *h* between the plates.

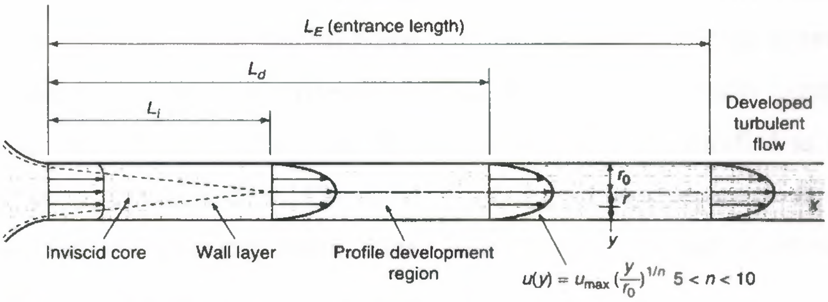


Figure 3.9 Velocity profile development in a turbulent pipe flow.

For a turbulent flow the situation is slightly different, as shown in Figure 3.9 for flow in a pipe. A developed flow results when all characteristics of the flow cease to change in the flow direction. The inviscid core exists followed by the velocity profile development region, which terminates at $x = L_d$. An additional length is needed, however for the detailed structure of the turbulent flow to develop. The detailed structure is important in certain calculations such as accurate estimates of wall heat transfer. For large Reynolds number flow ($Re>10^5$) in pipe where the turbulence fluctuations initiate near $x = 0$, tests have yielded to;

$$\frac{L_i}{D} \approx 10 \quad \frac{L_d}{D} \approx 40 \quad \frac{L_E}{D} \approx 120$$

For turbulent flow with Re = 4000 the foregoing developmental lengths would be substantially higher, perhaps five times the values listed.

3.8 CONCLUSION

In this chapter the different kinds of fluid motions such as: the viscous and inviscid flows, laminar and turbulent flows, incompressible and compressible flows, internal and external flows were discussed in details. Some common assumptions used to simplify a flow situation are related to fluid properties. A fluid flow may be broadly classified as either a viscous flow or an inviscid flow. A viscous flow can be classified as either a laminar flow or a turbulent flow. Classification of fluid flows separates flows into incompressible and compressible flows. Many important figures and equations were also presented in this chapter.

CHARTER 4

INTERNAL INCOMPRESSIBLE FLOW

4.1 INTRODUCTION

In this chapter the basic principles to a specific and important topic which is the flow of incompressible viscous fluids in pipes are discussed. The transport of a fluid (liquid or gas) in a closed conduit is extremely important in our daily operations. A brief consideration of the world around us will indicate that there are a wide variety of applications of pipe flow. Also some aspects of internal steady flow are discussed. The discussion is limited to incompressible fluids, that is to those for which the density is constant. Laminar and turbulent regimes are defined. The flow of a fluid in a pipe may be laminar flow or it may be turbulent flow depending on the critical Reynolds number.

4.2 GENERAL CHARACTERISTICS OF PIPE FLOW

Not all conduits used to transport fluid from one location to another are round in cross section, most of the common ones are so. These include typical water pipes, hydraulic hoses, and other conduits that are designed to withstand considerable pressure difference across their walls without causing distortion of the shape. Typical conduits of noncircular cross section include heating and air conditioning ducts that are often of rectangular cross section. Normally the pressure difference between the inside and outside of these ducts is relatively small.

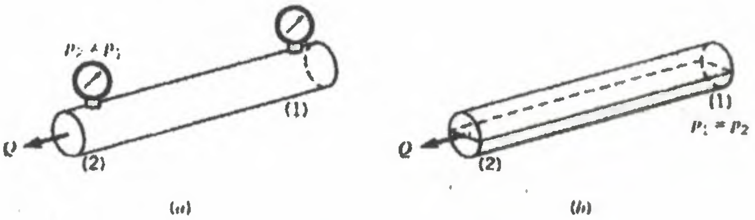
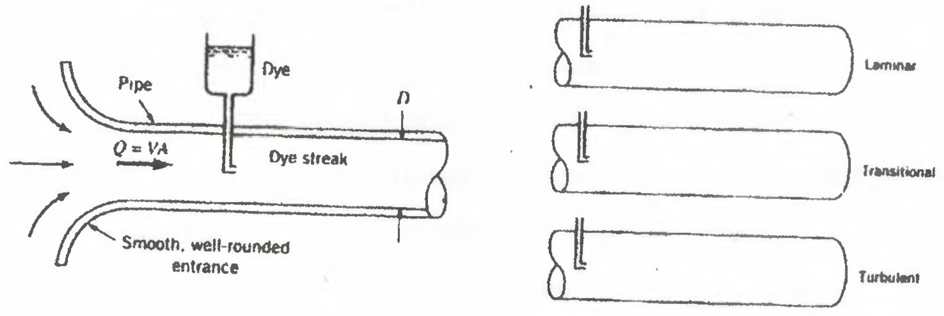


Figure 4.1 (a) pipe flow, (b) open channel flow.

For all flows involved in this chapter, pipe is completely filled with the fluid as shown in Figure 4.1 a. Thus, concrete pipe through which rainwater flows without completely filling the pipe as shown in Figure 4.1b will not considered.

4.3 LAMINAR AND TURBULENT FLOW

The flow of a fluid in a pipe may be laminar flow or it may be turbulent flow. A British Scientist and mathematician called Reynolds, was the first who distinguish the difference between these two classifications of flow by using simple apparatus as shown in Figure 4.2a. If water runs through a pipe of diameter D with an average velocity V, the following characteristics are observed by injecting neutrally buoyant dye as shown in Figure 4.2a. For small enough flow rate the dye streak will remain as a well-defined line as it flows along, with only slight blurring due to molecular diffusion of the dye into the surrounding water. For a somewhat larger intermediate flow rate the dye streak fluctuates in time and space, and intermittent bursts of irregular behavior appear along the streak. On the other hand, for large enough flow rates the dye streak almost immediately becomes blurred and spreads across the entire pipe in a random fashion. These three characteristics, denoted as laminar, transitional and turbulent flow respectively, are illustrated in Figure 4.2b.



(a) (b)

Figure 4.2 (a) fluctuations of turbulent flow, (b) flow characteristics.

The curves shown in Figure 4.3 represent the x-component of the velocity as function of time. As shown in Figure 4.3 the random fluctuations are observed for the turbulent flow, while for a laminar flow in a pipe there is only one component of velocity.

The Reynolds number ranges for which laminar, transitional, or turbulent pipe flows obtained cannot be precisely given. The actual transition from laminar to turbulent flow may take place at various Reynolds numbers, depending on how much the flow is disturbed by vibrations of the pipe, roughness of the entrance region and so on.

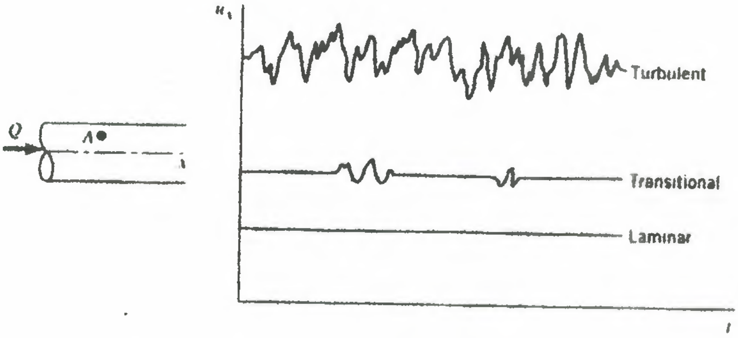


Figure 4.3 Time dependence of fluid velocity at a point.

4.4 CRITICAL REYNOLDS NUMBER

The critical Reynolds number is really indeterminate and depends upon the care taken to prevent any initial disturbance from affecting the flow. Laminar flow in circular pipes has been maintained up to values of Re as high as 50.000. However, in such cases this type of flow is inherently unstable, and the least disturbance will transform it instantly into turbulent flow. On the other hand, it is practically impossible for turbulent flow in a straight pipe to persist at values of Re much below 2000, because any turbulence that is set up will be damped out by viscous friction. Hence this lower value will be defined as the true critical Reynolds number. However, it is subject to slight variations. Its value will be higher in a converging pipe and lower in a diverging pipe than in a straight pipe. Also, its value will be less for flow in a curved pipe than in a straight one, and even for a straight uniform pipe its value may be as low as 1000, where there is excessive roughness. However, for normal cases of flow in straight pipes of uniform diameter and usual roughness, the critical value may be taken as $R_{cr} = 2000$.

4.5 EFFECT OF VISCOSITY

In laminar flow, in which inertia or momentum of the fluid is small, the viscous effect is able to penetrate farther into the cross section from the wall than it can in turbulent flow. Stated another way, in turbulent flow, in which the viscous effects are small, the momentum or inertia of the flow is able to penetrate farther outward toward the wall from the centerline than it can in laminar flow. This penetration of momentum or inertia is called the momentum transport phenomenon.

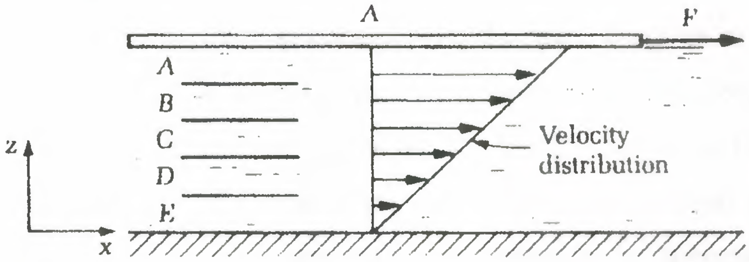
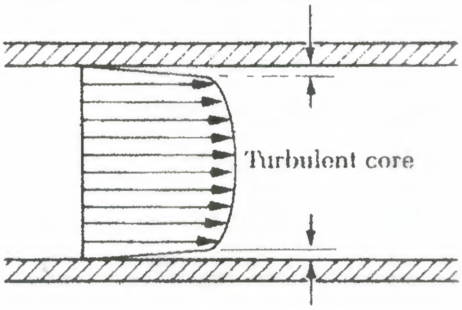


Figure 4.4 Layers of fluid flow between parallel plates.

Consider the case of a fluid between two parallel plates with the upper plate moving as shown in Figure 4.4. The upper plate has fluid adhering to it owing to friction. The plate exerts a shear stress on the particles in layer A. This layer in turn exerts a shear stress on layer B and so on. It is the x component of velocity in each layer that causes this shear stress to be propagated in the negative z direction. That is, the A layer pulls the B layer along and so forth. As this shear stress approaches the stationary wall, movement is retarded by the effect of zero velocity at the bottom propagating upward. That is, the E layer retards the D layer and so on. The resultant effect on velocity is the distribution sketched in Figure 4.4.



Laminar sublayer

Figure 4.5 Laminar sublayer in turbulent pipe flow.

In turbulent flow, the velocity at a stationary wall is zero. Near the wall, then, there must be a region of flow that is laminar. This region is called the laminar sublayer, and the flow in the remainder of the cross section is called the turbulent core. Both regions are illustrated for flow in a pipe in Figure 4.5.

4.6 ENTRANCE CONDITIONS IN LAMINAR FLOW

In the case of a pipe leading from a reservoir, if the entrance is rounded so as to avoid any initial disturbance of the entering stream, all particles will start to flow with the same velocity, except for a very thin film in contact with the wall. Particles in contact with the wall have zero velocity, but the velocity gradient is here extremely steep, and, with this slight exception, the velocity is uniform across the diameter, as shown in Figure 4.4. As the fluid progresses along the pipe, the streamlines in the vicinity of the wall are slowed down by friction emanating from the wall, but since Q is constant for successive sections, the velocity in the center must be accelerated, until the final velocity profile is a parabola, as shown in Figure 4.6.

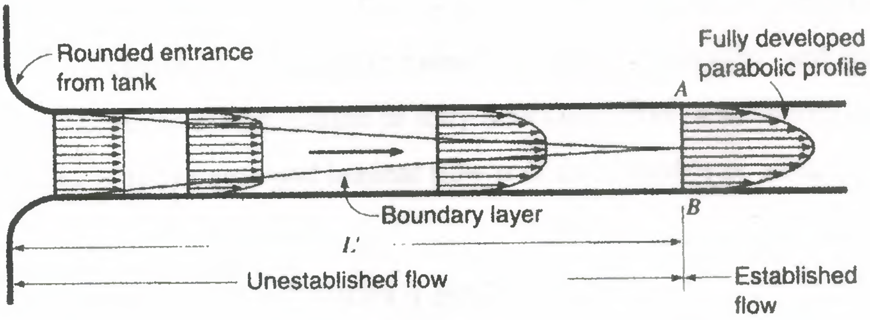


Figure 4.6 Velocity profiles and development of the boundary layer along a pipe in laminar flow.

In the entry region of length L' the flow is unestablished, that is the velocity profile is changing. At section *AB* the boundary layer has grown until it occupies the entire section of the pipe. At this point, for laminar flow, the velocity profile is a perfect parabola. Beyond section *AB,* the velocity profile does not change, and the flow is known as established flow.

At the entrance to the pipe the velocity is uniformly V across the diameter, except for an extremely thin layer next to the wall. Thus at the entrance to the pipe the kinetic energy per unit weight is practically $V^2/2g$. Hence in the distance L' there is a continuous increase in kinetic energy accompanied by a corresponding decrease in pressure head. Therefore at a distance L' from the entrance the piezometric head is less than the static value in the reservoir by $2V^2/2g$ plus the friction loss in this distance.

4.7 FULLY DEVELOPED LAMINAR FLOW

As indicated in the previous section, the flow in long, straight, constant diameter sections of a pipe becomes fully developed. That is, the velocity profile is the same at any cross section of the pipe. Although this is true whether the flow is laminar or turbulent, the details of the velocity profile are quite different for these two types of flow. Knowledge of the velocity profile can lead directly to other useful information such as pressure drop, head loss, and flow rate.

If the flow is not fully developed, a theoretical analysis becomes much more complex and is outside the scope of this text. If the flow is turbulent, a rigorous theoretical analysis is as yet not possible. Although most flows are turbulent rather than laminar, and many pipes are not long enough to allow the attainment of fully developed flow, a theoretical treatment and full understanding of fully developed laminar flow is of considerable importance.

4.8 FULLY DEVELOPED TURBULENT FLOW

Since the turbulent pipe flow is actually more likely to occur than laminar flow in practical situations, it is necessary to obtain similar information for turbulent pipe flow. However, turbulent flow is a very complex process. Numerous persons have devoted considerable effort in attempting to understand the variety of baffling aspects of turbulence. Although a considerable amount of the knowledge about the topic has been developed, the field of turbulent flow still remains the least understood area of fluid mechanics.

4.9 TRANSITION FROM LAMINAR TO TURBULENT FLOW

Flows are classified as laminar or turbulent. For any flow geometry, there is one or more dimensionless parameter such that with this parameter value below a particular value the flow is laminar, whereas with the parameter value larger than a certain value the flow is turbulent. For pipe flow the value of the Reynolds number must be less than approximately 2000 for laminar flow and greater than approximately 4000 for turbulent flow as shown in Figure 4.7. For flow along a flat plate the transition between laminar and turbulent flow occurs at a Reynolds number of approximately 500.000, where the length term in the Reynolds number is the distance measured from the leading edge of the plate.

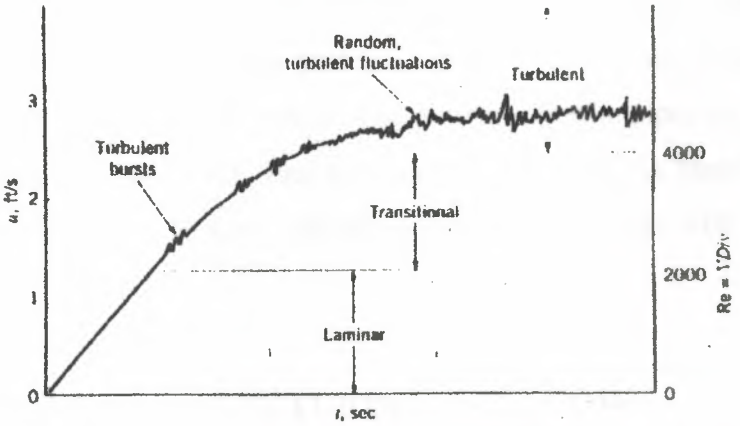


Figure 4.7 Transition from laminar to turbulent flow in a pipe.

Consider a long section of pipe that is initially filled with fluid at rest. As the valve is opened to start the flow, the flow velocity and, hence, the Reynolds number increase from zero (no flow) to their maximum steady state flow values as shown in Figure 4.7

Assume this transient process is slow enough so that unsteady effects are negligible. For an initial time period the Reynolds number is small enough for laminar flow to occur. At some time the Reynolds number reaches 2000, and the flow begins its transition to turbulent conditions. Intermittent spots or bursts of turbulence appear. As the Reynolds number is increased the entire flow field becomes turbulent. The flow remains turbulent as long the Reynolds number exceeds approximately 4000.

Mixing processes and heat and mass transfer processes are considerably enhanced in turbulent flow compared to laminar flow. This is due to the macroscopic scale of the randomness in turbulent flow. Laminar flow, on the other hand, can be thought of as very small but finite sized fluid particles flowing smoothly in layers, one over another. The only randomness and mixing take place on the molecular scale and result in relatively small heat, mass, and momentum transfer rates.

Without turbulence it would be virtually impossible to carry out life, as we now know it. In some situations turbulent flow is desirable. To transfer the required heat between a solid and an adjacent fluid would require an enormously large heat exchanger if the flow were laminar. Similarly, the required mass transfer of a liquid state to a vapor state would require very large surfaces if the fluid flowing past the surface were laminar rather than turbulent. In other situations laminar flow is desirable. The pressure drop in pipes can be considerably lower if the flow is laminar rather than turbulent. Fortunately, the blood flow through a person's arteries is normally laminar, except in the largest arteries with high blood flow rates.

4.10 VISCOUS SUBLAYER IN TURBULENT FLOW

For laminar flow, if the fluid enters with no initial disturbance, the velocity is uniform across the diameter except for an exceedingly thin film at the wall, in as much the velocity net to any wall is zero. But as flow proceeds down the pipe, the velocity profile changes because of the growth of a laminar boundary layer, which continues until the boundary layers from opposite sides meet at the pipe axis and then there is fully developed laminar flow.

If the Reynolds number is above the critical value, so that the developed flow is turbulent, the initial condition is much like that in Figure 4.6. But as the laminar boundary layer increases in thickness, a point is soon reached where a transition occurs and the boundary layer becomes turbulent. This turbulent boundary layer generally increases in thickness much more rapidly, and soon the two layers from opposite sides meet at the pipe axis, and there is then fully developed turbulent flow.

As velocity must be zero at a smooth wall, turbulence there is inhibited so that a laminar-like sublayer occurs immediately next to the wall. However, the adjacent turbulent flow does repeatedly induce random transient effects that momentarily disrupt this sublayer, even though they are strongly damped out. Because it is therefore not a true laminar layer, and because shear in this layer is predominantly due to viscosity alone, it is called a viscous sublayer as shown in Figure 4.8.

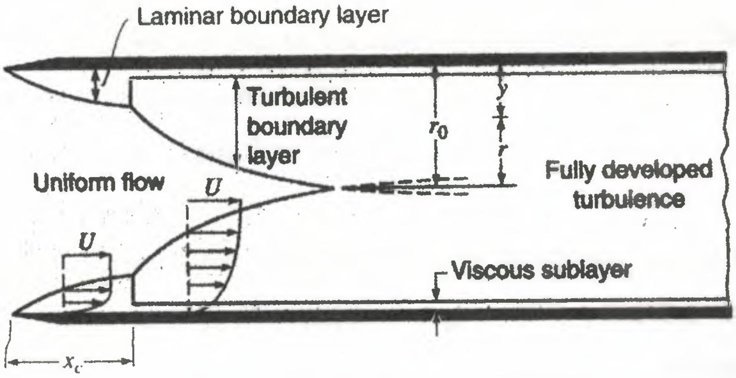


Figure 4.8 Development of boundary layer in a pipe where fully developed flow is turbulent.

This viscous sublayer is extremely thin, usually only a few hundredths of a millimeter, but its effect is great because of the very steep velocity gradient within it. At a greater distance from the wall the viscous effect becomes negligible, but the turbulent shear is then large.

4.11 CONCLUSION

In this chapter the general characteristics of pipe flow were presented. Laminar and turbulent phenomena, critical Reynolds number, effect of viscosity, the entrance conditions in laminar and turbulent flows, and the transition from laminar to turbulent flow were discussed. The Newton viscosity law was used for the laminar flow. The three zones of pipe flow, which are: the smooth pipe, the rough pipe, and the transition were also explained. Also some aspects of internal steady flow were discussed. The discussion in this chapter is limited to incompressible fluids, that is to those for which the density is constant. Laminar and turbulent regimes were also defined. The velocity profiles and the boundary layers for both laminar and turbulent flows were also explained with some figures.

CHAPTER 5

FLOW IN PIPES

5.1 INTRODUCTION

Flow in pipes is a very important part of the study of fluid mechanics. This chapter presents the pressure and shear distribution, velocity profile, pipe roughness, and the major and minor losses observed during fluids flow in pipes.

Gravity and pressure forces affect directly the fully developed steady flow. In non-fully developed flow regions, such as the entrance region of a pipe, the fluid accelerates or decelerates as it flows. In fully developed turbulent regions flow in can be broken in to three layers: the viscous sublayer, the overlap region, and the outer turbulent layer throughout the center portion of the flow.

Losses can be divided in to two categories: the first one is those due to wall shear in pipe elements and are distributed along the length of pipe elements, the second one is those due to pipe components and are treated as discrete discontinuities in the hydraulic grade line and the energy grade line and are commonly referred to as minor losses.

5.2 PRESSURE AND SHEAR STRESS

Fully developed steady flow in a constant diameter pipe may be driven by gravity or pressure forces. For horizontal pipe flow, gravity has no effect except for a hydrostatic pressure variation across the pipe that is usually negligible. Viscous effects provide the restraining force that exactly balances the pressure force by allowing the fluid to flow through the pipe with no acceleration. If viscous effects were absent in such flows, the pressure would be constant throughout the pipe, except for the hydrostatic variation.

In non-fully developed flow regions, such as the entrance region of a pipe, the fluid accelerates or decelerates as it flows. Thus, in the entrance region there is a balance between pressure, viscous, and inertia (acceleration) forces. The result is pressure distribution along the horizontal pipe as shown in Figure 5.1. The magnitude of the pressure gradient, dp/dx is larger in the entrance region than in the fully developed region.

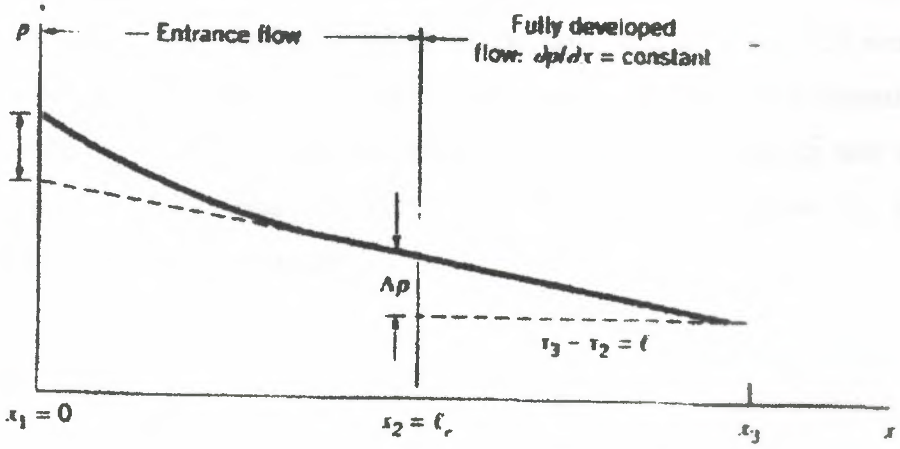


Figure 5.1 Pressure distribution along the horizontal pipe.

The fact that there is a nonzero pressure gradient along the horizontal pipe is a result of viscous effects. If the viscosity were zero, the pressure would not vary with x, the need for the pressure drop can be viewed from two different standpoints. If the pipe is not horizontal, the pressure gradient along it is due in part to the component of weight in that direction. This contribution due to the weight either enhances or retards the flow, depending on whether the flow is downhill or uphill.

The nature of the pipe flow is strongly dependent on whether the flow is laminar or turbulent. This is a direct consequence of the differences in the nature of the shear stress in laminar and turbulent flows. The shear stress in turbulent flow is largely a result of momentum transfer among the randomly moving, finite-sized bundles of fluid particles.

5.3 VELOCITY PROFILE

The time-average velocity profile in a pipe is quite sensitive to the magnitude of the average wall roughness height *e* as sketched in Figure 5.2. All materials are rough when viewed with sufficient magnification, although glass and plastic are assumed to be smooth with $e = 0$. Note that, the laminar shear is significant only near the wall in the viscous wall layer with thickness. If the thickness is sufficiently large, it submerges the wall roughness elements so that they have negligible effect on the flow, it is as if the wall were smooth. Such a condition is often referred to as being hydraulically smooth. If the viscous wall layer is relatively thin, the roughness elements protrude out of this layer and the wall is rough as shown in Figure 5.2. The relative roughness and the Reynolds number can be used to determine if a pipe is smooth or rough.

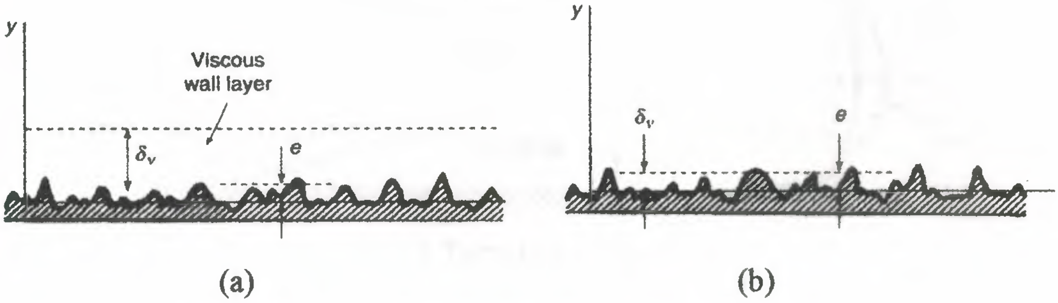


Figure 5.2 (a) A smooth wall and (b) a rough wall.

5.4 TURBULENT VELOCITY PROFILE

Considerable information concerning turbulent velocity profiles has been obtained through the use of dimensional analysis, experimentation, and semi empirical theoretical efforts. Fully developed turbulent flow in a pipe can be broken into three regions which are characterized by their distances from the wall: the viscous sublayer very near the pipe wall, the overlap region, and the outer turbulent layer throughout the center portion of the flow. Within the viscous sublayer the viscous shear stress is dominant compared with the turbulent stress, and the random, eddying nature of the flow is essentially absent.

In the outer turbulent layer the Reynolds stress is dominant, and there is considerable mixing and randomness to the flow. The character of the flow within these two regions is entirely different. For example, within the viscous sublayer the fluid viscosity is an important parameter while the density is not important.

As shown in Figure 5.3 the turbulent profiles are much flatter than the laminar profile and that this flatness increases with Reynolds number (i.e, with n). Reasonable approximate results are often obtained by using the inviscid Bernoulli equation and by assuming a fictitious uniform velocity profile. Since most flows are turbulent and turbulent flow tends to have nearly uniform velocity profiles, the usefulness of the Bernoulli equation and the uniform profile assumption is not unexpected. Of course, many properties of the flow cannot be accounted for without including viscous effect.

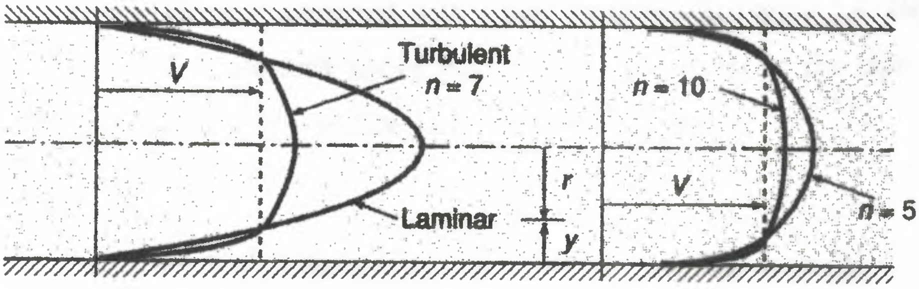


Figure 5.3 Turbulent velocity profile.

5.5 HYDRAULIC AND ENERGY GRADE LINES

Hydraulic and energy grade lines give a graphic presentation of the flow quantities in a particular configuration. The hydraulic grade line is a plot of pressure versus distance, the energy grade line is a plot of the sum of pressure and kinetic energy as a function of distance. These concepts are best illustrated by example.

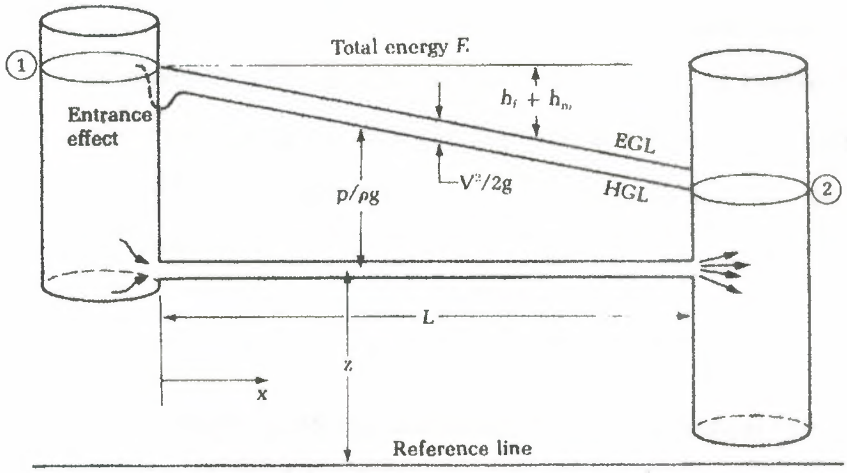


Figure 5.4 Energy lines for a piping system.

Consider two large reservoirs connected with a pipe as shown in Figure 5.4. Because one liquid reservoir surface is elevated above the other, a flow exists in the pipe. The total mechanical energy in the system at section 1 can be written as;

$$E_1 = \frac{P_1}{pg} + \frac{V_1^2}{2g} + Z_1$$

The total mechanical energy at section 2 is;

$$E_2 = \frac{P_2}{pg} + \frac{V_2^2}{2g} + Z_2$$

The above equations are related as;

$$E_1 = E_2 + h_f + h_m$$

Where;

h_f: the friction losses

h_m: the minor losses

The total energy including friction and minor losses must be constant, so the plot of total energy versus distance along the pipe is a horizontal line as shown in Figure 5.4. The plot of $p/\rho g$ versus L is the hydraulic grade line (HGL). The curve of $V^2/2g$ versus L is the energy grade line (EGL). The difference between the energy grade line and the total energy line represents frictional losses.

5.6 PIPE ROUGHNESS

The roughness of a pipe could be measured and described by geometrical factors, and it has been proved that the friction is dependent not only upon the size and shape of the projections, but also upon their distribution or spacing. The most efforts in this direction were made by a German engineer Nikuradse. He coated several different sizes of pipe with sand grains that had been sorted by sieving so as to obtain different sizes of grain of reasonably uniform diameters. The diameters of the sand grains may be represented by *e*, which is known as the absolute roughness. Dimensional analysis of pipe flow showed that for a smooth-walled pipe the friction factor *f* is a function of Reynolds number. A general approach, including *e* as a parameter, reveals that $f = \Phi(R, e/D)$. The term *e*/D is known as the relative roughness.

In the case of artificial roughness such as this, the roughness is uniform, whereas in commercial pipes it is irregular both in size and in distribution. However, the roughness of commercial pipe may be described by *e*.

It has been found for smooth-pipe flow;

$$\frac{1}{\sqrt{f}} = 2\log\left(\frac{R_e\sqrt{f}}{2.51}\right)$$

Where;

f: the friction factor
R_e: the Reynolds number

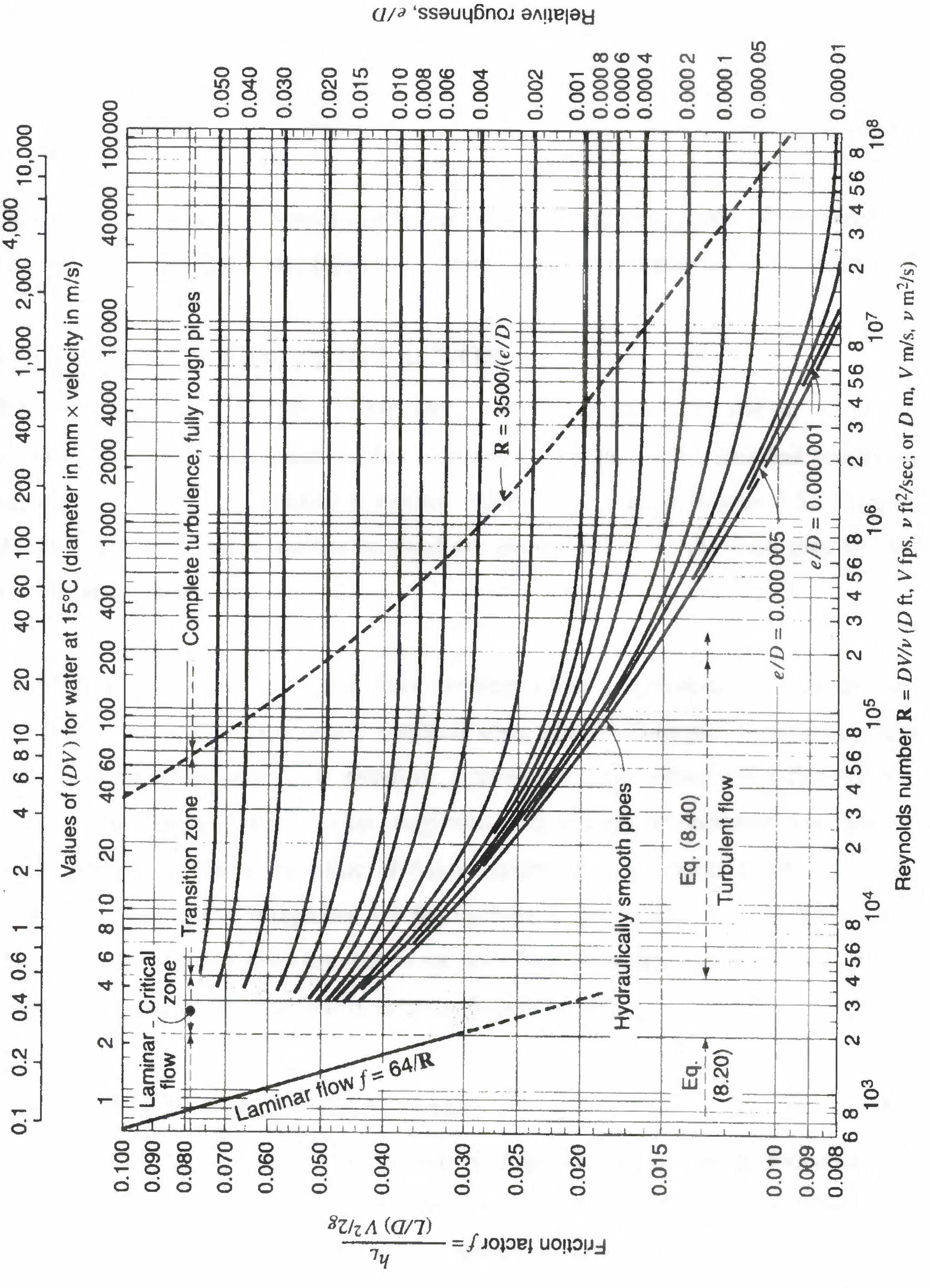


Figure 5.5 Moody chart for pipe friction.

While for fully rough pipe flow;

$$\frac{1}{\sqrt{f}} = 2\log\left(\frac{3.7}{e/D}\right)$$

The values of f from this equation correspond to the right-hand side of the chart (Figure 5.5), where the curves become horizontal. These values are sometimes referred to as $f_{\min}$.

5.7 CHART FOR FRICTION FACTOR

The preceding equations for f have been very inconvenient to use in a number of circumstances, to be discussed further in coming sections. In the past this inconvenience was partly overcome by reading numerical values from a chart (Figure 5.5), prepared by Moody in 1944. All the quantities involved are dimensionless, so the chart may be used for both BG and SI unit systems.

The Moody chart, and the various flow conditions that it represents, may be divided into four zones: the laminar flow zone, a critical zone where values are uncertain because the flow might be either laminar or turbulent, a transition zone, where f is a function of both Reynolds number and relative pipe roughness, and a zone of complete turbulence (fully rough pipe flow), where the value of f is independent of Reynolds number and depends solely upon the relative roughness. On the right-hand side of the chart the given values of e/D correspond to the curves and not to the grid. Note how their spacing varies. The lowest of the curves in the transition zone is the smooth-pipe curve.

5.8 CALCULATION OF HEAD LOSS

Total head loss, h_{lT}, is regarded as the sum of major losses, h_{lm}, due to frictional effects in fully developed flow in constant-area tubes, and minor losses, h_l, due to entrances, fittings, area changes, and so on. Consequently, we consider the major and minor losses separately.

5.8.1 MAJOR LOSSES: FRICTION FACTOR

The energy balance can be used to evaluate the major head loss. For fully developed flow through a constant-area pipe, h $_{lm}$ = 0 and thus we get;

$$\frac{P_1 - P_2}{p} = g(z_2 - z_1) + h_l$$

If the pipe is horizontal, then z $_2$ =z $_1$ and we get;

$$\frac{P_1 - P_2}{p} = \frac{\Delta p}{p} = h_l$$

Thus the major head loss can be expressed as the pressure loss for fully developed flow through a horizontal pipe of constant area.

Since head loss represents the energy converted by frictional effects from mechanical to thermal energy, head loss for fully developed flow in a constant-area duct depends only on the details of the flow through the duct. Head loss is independent of pipe orientation.

In laminar flow, the pressure drop may be computed analytically for fully developed flow in a horizontal pipe, thus;

$$\Delta p = 32 \frac{L}{D} \frac{\mu \overline{V}}{D}$$

Where;

$\overline{V}$: the average flow velocity
D: the pipe diameter
µ: the fluid viscosity

Substitute Δp in the head loss equation, we get;

$$h_l = \left(\frac{64}{\text{Re}}\right)\frac{L}{D}\frac{\overline{V}^2}{2}$$

In fully developed turbulent flow, the pressure drop Δ_P, due to friction in a horizontal constant-area pipe is known to depend on pipe diameter D, pipe length L, pipe roughness, *e*, average flow velocity $\overline{V}$, fluid density p, and fluid viscosity μ.

In functional form;

$$\Delta p = \Delta p\left(D, L, e, \overline{V}, p, \mu\right)$$

After applying dimensional analysis and approximations we get;

$$h_l = \left(\frac{64}{\text{Re}}\right)\frac{L}{D}\frac{\overline{V}^2}{2} = f\frac{L}{D}\frac{\overline{V}^2}{2}$$

Consequently, for laminar flow;

$$f_{laminar} = \frac{64}{\text{Re}}$$

Thus, in laminar flow the friction factor is a function of Reynolds number only, it is independent of roughness.

The Reynolds number in a pipe may be changed most easily by varying the average flow velocity. If the flow in a pipe is originally laminar, increasing the velocity until the critical Reynolds number is reached causes transition to occur; the laminar flow gives way to turbulent flow. As the Reynolds number is increased above the transition value, the velocity profile continues to become fuller. However, as the Reynolds number increases, the velocity profile becomes still fuller. The size of the thin viscous sublayer near the tube wall decreases. As roughness elements begin to poke through this layer, the effect of roughness becomes important, and the friction factor becomes a function of both the Reynolds number and the relative roughness. At very large Reynolds number, most of the roughness elements on the tube wall protrude through the viscous sublayer, the drag and, hence, the pressure loss, depend only on the size of the roughness element.

5.8.2 MINOR LOSSES IN TURBULENT FLOW

Losses due to the local disturbances of the flow in conduits such as changes in cross section, projecting gaskets, elbows, valves, and similar items are called minor losses. In the case of a very long pipe or channel, these losses are usually insignificant in comparison with the fluid friction in the length considered. But if the length of pipe or channel is very short, these so-called minor losses may actually be major losses. Thus, in the case of the suction pipe of a pump, the loss of head at entrance, especially if a strainer and a foot valve are installed, may be very much greater than the friction loss in the short inlet pipe.

Head loss in decelerating flow is much larger than that in accelerating flow. In addition, head loss generally increases with an increase in the geometric distortion of the flow. Though the causes of minor losses are usually confined to a very short length of the flow path, the effects may not disappear for a considerable distance downstream. Thus an elbow in a pipe may occupy only a small length, but the disturbance in the flow will extend for a long distance downstream. The most common sources of minor loss are described in the remainder of this chapter. Such losses may be represented in one of two ways. They are expressed as $kV^2/2g$, where k is the loss coefficient constant.

EXAMPLE: FLOW INSIDE PIPE

Water at 0.02 m^3/s flows through 350 m of a cast iron pipe. Given that: the diameter of the pipe is 20.27 cm, its area is 322.7 cm^2, and the average wall roughness is $e = 0.025$ cm, determine the head loss if the water temperature is 22°C.

SOLUTION:

For water at 22°C: $v = 9.569 \times 10^{-7}$ m^2/s.

The velocity can be calculated as;

$$V = \frac{Q}{A} = \frac{0.02 m^3/s}{0.03227 m^2} = 0.62 \text{ m/s}$$

Then the Reynolds number is;

$$\mathrm{Re} = \frac{VD}{v} = \frac{(0.62 m/s)(0.2027 m)}{9.567 \times 10^{-7} m^2/s} = 1.31 \times 10^5$$

Since Re > 2000, then the flow is turbulent.

By taking *e* as 0.025 cm, then;

$$\frac{e}{D} = \frac{0.025 cm}{20.27 cm} = 0.0012$$

On the $\frac{e}{D}$ = 0.0012 line of Figure 5.5, follow to the left from the turbulence zone until the Re = 1.31×10^5 point is reached. At this intersection, the friction factor *f is* 0.022.

By substitution the above values into the equation of head loss, we obtain;

$$h_l = \frac{fL\overline{V}^2}{2D} = \frac{fLV^2}{2gD} = \frac{(0.022)(350m)(0.62m/s)^2}{2(9.81m/s^2)(0.2027m)} = 0.744 \text{ m of water.}$$

5.9 LOSS OF HEAD AT ENTRANCE

As shown in Figure 5.6 it may be seen that as fluid from the reservoir enters the pipe, the streamlines continue to converge. As a result the cross section with maximum velocity and minimum pressure was found at B.

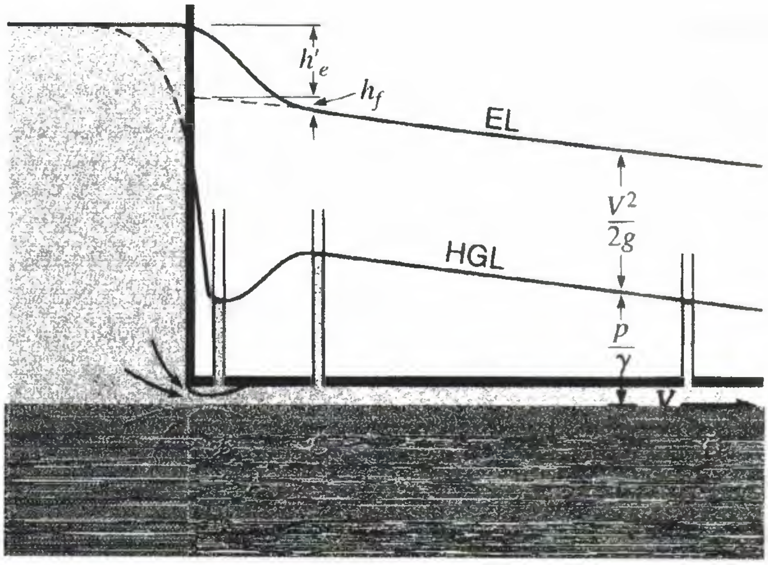


Figure 5.6 Conditions at entrance.

At B, the contracted flowing stream is surrounded by fluid that is in a state of turbulence but has very little forward motion. Between B and C the fluid is in a very disturbed condition because the stream expands and the velocity decreases while the pressure rises. From C to D the flow is normal. It is seen that the loss of energy at entrance is distributed along the length AC,

The loss of head at entrance may be expressed as;

$$h'_e = k_e \frac{V^2}{2g}$$

Where;

V: the mean velocity in the pipe
k*e*: the loss coefficient.

The entrance loss is caused primarily by the turbulence created by the enlargement of the stream after it passes section B, and this enlargement in turn depends upon how much the stream contracts as it enters the pipe. Thus it is very much affected by the conditions at the entrance to the pipe. Values of the entrance-loss coefficients have been determined experimentally. If the entrance to the pipe is well rounded or bell-mouthed then there is no contraction of the stream entering and the coefficient of loss is correspondingly small. For a flush or square-edged entrance k_e has a value of about 0.5. The degree of the contraction depends upon how far the pipe may project within the reservoir and also upon how thick the pipe walls are, compared with its diameter.

5.10 LOSS DUE TO CONTRACTION

Sudden Contraction

The phenomena attending the sudden contraction of a flow are shown in Figure 5.7. It is noted that in the corner upstream at section C there is a rise in pressure because the streamlines here are curving, so that the centrifugal action causes the pressure at the pipe wall to be greater than in the center of the stream. The dashed line indicates the pressure variation along the centerline streamline from sections B to C. From C to E, the conditions are similar to those described for entrance.

Table 5.1 Loss coefficients for sudden contraction.

D_2/D_1	**0.0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**
k_c	0.5	0.45	0.42	0.39	0.36	0.33	0.28	0.22	0.15	0.06	0.0

The loss of head for a sudden contraction h'_c may be represented by;

$$h'_c = k_c \frac{V_2^2}{2g}$$

Where k_c has the values given in Table 5.1.

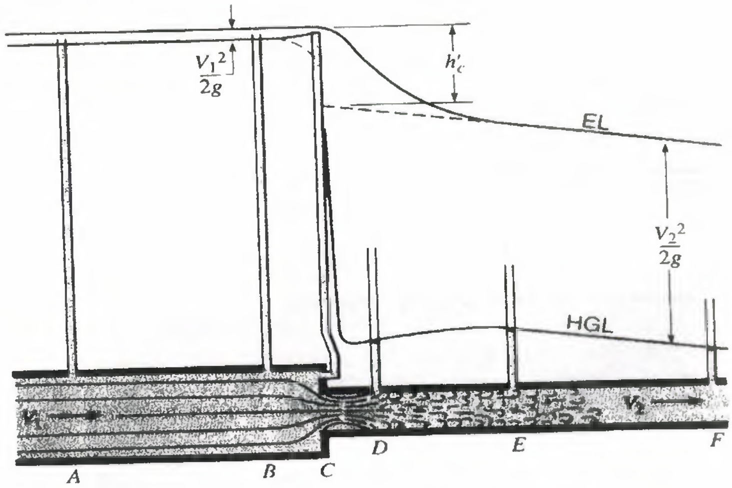


Figure 5.7 Loss due to sudden contraction.

5.11 LOSS DUE TO EXPANSION

Sudden Expansion

The conditions at a sudden expansion are shown in Figure 5.8. There is a rise in pressure because of the decrease in velocity, but this rise is not so great as it would be if it were not for the loss in energy. There is a state of excessive turbulence from C to F, beyond which the flow is normal. The drop in pressure just beyond section C, which was measured by a piezometer not shown in the illustration, is due to the fact that the pressures at the wall of the pipe are in this case less than those in the center of the pipe because of centrifugal effects.

Figures 5.7 and 5.8 are both drawn to scale from test measurements for the same diameter ratios and the same velocities, and show that the loss due to sudden expansion is greater than the loss due to a corresponding contraction. This is so because of the inherent instability of flow in an expansion where the diverging paths of the flow tend to encourage the formation of eddies within the flow

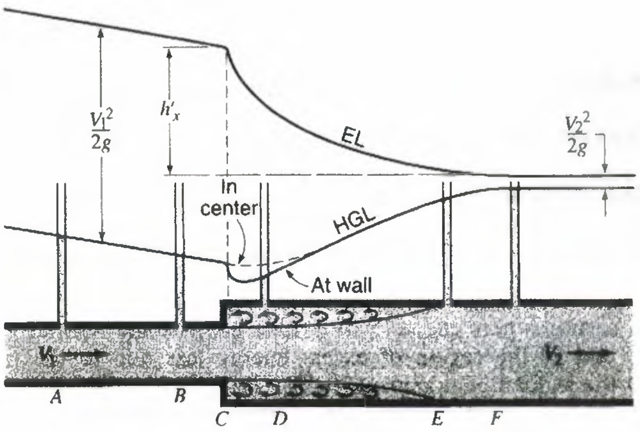


Figure 5.8 Loss due to sudden enlargement.

5.12 LOSS IN PIPE FITTINGS

The loss of head in pipe fittings may be expressed as $kv^2/2g$, where V is the velocity in a pipe of the nominal size of the fitting. Typical values of k are given in Table 5.2. As an alternative, the head loss due to a fitting may be found by increasing the pipe length by using values of L/D given in the table. It must be recognized that these fittings create so much turbulence that the loss caused by them is proportional to V^2, and hence this latter method should be restricted to the case where the pipe friction it self is in the zone of complete turbulence. For very smooth pipes, it is better to use the *k* values when determining the loss through fittings.

Table 5.2 Values of loss factors for pipe fittings.

Fitting	k	L/D
Globle valve, wide open	10	350
Angle valve, wide open	5	175
Close-return bend	2.2	75
T, through side outlet	1.8	67
Short-radius elbow	0.9	32
Medium-radius elbow	0.75	27
Long-radius elbow	0.6	20
45^0 elbow	0.42	15
Gate valve; wide open	0.19	7
half open	2.06	72

5.13 PIPE BENDS LOSSES

The head loss of a bend is larger than for fully developed flow through a straight section of equal length. The additional loss is primarily the result of secondary flow, and is represented most conveniently by an equivalent length of straight pipe. The equivalent length depends on the relative radius of curvature of the bend, as shown in Figure 5.9a for 90° bends.

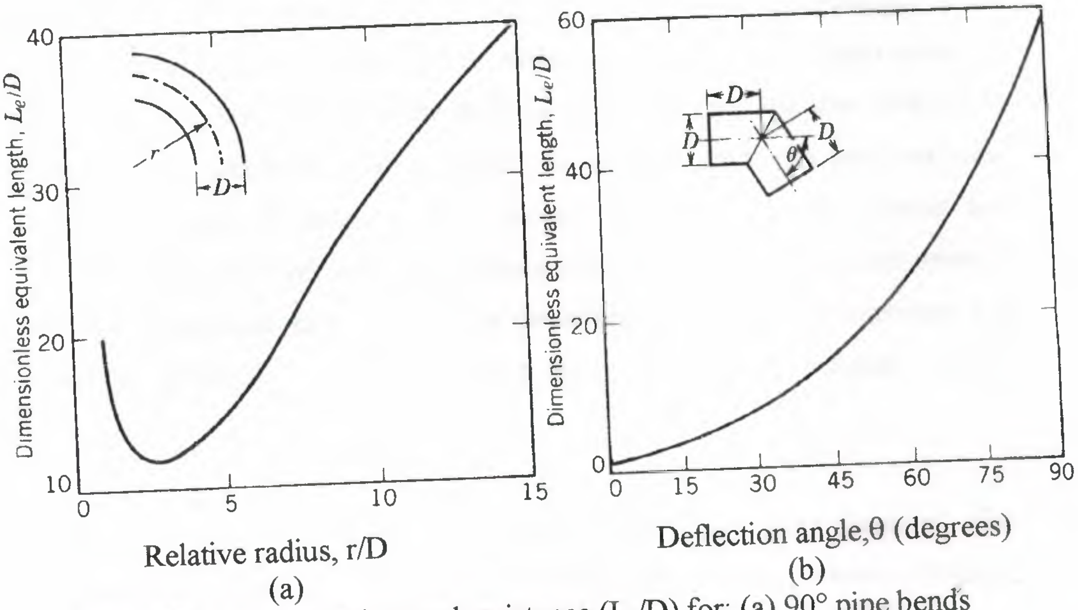


Figure 5.9 Representative total resistance (L_e/D) for; (a) 90° pipe bends and flanged elbows, and (b) miter bends.

Because they are simple and inexpensive to erect in the field, miter bends often are used, especially in large pipe systems. Design data for miter bends are given in Figure 5.9b.

5.14 CONCLUSION

In this chapter pressure and shear stress, velocity profile, hydraulic and energy grade lines, and pipe roughness were explained. The major and the minor losses including the loss due to contraction, the loss due to expansion, the loss in pipe fittings and the pipe bends losses were discussed where they affect the internal flow in pipes. Many figure and tables were presented in this chapter. The moody chart for pipe friction was shown. Also two tables were used in this chapter, the first one for calculating the loss coefficients for sudden contraction and the second one for calculating the values of the loss factors for pipe fittings.

CONCLUSION

Throughout this project the definition of fluid, the properties of fluids, the classification of fluid flows, and the fluid dynamics in pipes were discussed. In the first chapter a sketch of the historical development of fluid mechanics was given. Fluid was defined from a mechanics view point. A table for SI units was given in this chapter that summarizes the units needed in fluid mechanics. In the second chapter fluid properties such as: viscosity, surface tension, vapor pressure, the conservation laws needed in the study of fluid mechanics and their relations to thermodynamic properties were explained. In the third chapter, a brief overview of different types of flows, such as viscous and inviscid flows, laminar and turbulent flows, incompressible and compressible flows, and internal and external flows were discussed. In a viscous flow the effects of viscosity are important and cannot be ignored while in an inviscid flow the effect of viscosity can be neglected.

In the fourth chapter some aspects of internal steady flow were discussed. The discussion is limited to incompressible fluids. Laminar and turbulent regimes were defined. The flow of a fluid in a pipe may be laminar flow or it may be turbulent flow depending on the critical Reynolds number. The Newton viscosity law was used for the laminar flow. In the fifth chapter the pressure and shear distribution, velocity profile, pipe roughness, and the major and minor losses observed during fluids flow in pipes were explained. The concept of friction and a friction factor was explained. Because the fluid velocity influences the friction factor, it was necessary to show the velocity distribution for circular pipe flow.

Since fluid mechanics are of great importance for scientists and engineers, many researches and studies are continued to discover more and more about fluid mechanics. In addition more advanced techniques are involved with the aid of computers in order to make the study of fluid dynamics precise and accurate.

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