NEAR EAST UNIVERSITY

Faculty of Engineering

Department of Mechanical Engineering

LAMINARAND TURBULENT FLOW; INTERNAL AND EXTERNAL FCOW

Graduation Project
ME-400

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NICOSIA - 2002

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CHAPTERIV

ľ1.OW OVER Il\fl\1ERSED BODIES

ABSTRACT

The aim of this project is to present the main characteristics of flows, its behavior and the major effects that influencethe flow.
In the first chapter some füridafri.erifalaspects of fluid including its properties, fluid kinematics, and the factors effecting will be discuses. The flow concepts, classification and majorfactorsa:ffectin:g the flow, including a briefabout dimensional and dimensionless arialysis.
In the next chapter it will discuses the applications for additional important notions such as bouridarylayer,trarisitiori from laminarto turbulent, turbulence modeling, and flow separation are Intrcdırced as pipe flow .And in the chapter as an external flow.

ACKNOWLEDGEMENTS

I am proudly presenting this thesis asa senior project to face the requirements ofthe Mechanical Engineering Department in the Near East University.

First I would like to deeply thank my supervisor Assist. **Prof. Dr Guner Ozmen** for her invaluable advice and belief in myself over the course of this Graduation Project.

Second I thank.my family for their constant encouragement and support during my whole life.

Last but not leastlwould also like to thank all ofmy friends specially M. Badder and M. Jarkas who were always available for my assistance throughout this project.

CHAPTERI

FLUID PROPERTIES

The engineering science offluid mechanics has been developed through an understanding offluid properties, the application of the basic laws of mechanics and thermodynamics, and orderly experimentation. The properties of density and viscosity play principal roles in open- and closed-channel flow.

1.1 DEFINITION OF A FLUID

A fluid *is* a substance *that* deforms *continuous1y* when subjected *to* a shear stress, no matter how small that shear stress may be. A shear force is the force component tangent to a surface, and this force divided by the area of the surface is the average shear stress over the area. Shear stress at a point is the limiting value of shear force to area as the area is reduced to the point.

The fluid in immediate contact with a solid boundary has the same velocity as the boundary: i.e., there is no slip at the boundary. This is an experimental fact which has been verified in countless tests with various kinds of fluids and boundary materials. The fluid in the area abed flows to the new position oh - each fluid particle moving parallel to the plate and the velocity u varying uniformly from zero at the stationary plate to U at the upper plate. In which g is the proportionality factor and includes the effect of the particular fluid. If -r = F/A for the shear stress,

$$-r=\mu-\frac{u}{t}$$

The ratio U/t is the angular velocity of line ab, or it is the rate of angular deformation of the fluid, i.e., the rate of decrease of anglehad. The angular velocity may also be written du/dy, as both U/t du/dy express the velocity change divided by the distance over which the change occurs. However, du/dy is more general, as it holds for situations in which the angular velocity and shear stress change with y.

The velocity gradient du/dy may also be visualized as the rate at which one layer moves relative to an adjacent layer. In differential form

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

is the relation between shear stress and rate of angular deformation for one-dimensional flow ofa fluid. The proportionality factor g is called the v/scanty of the fluid, and equation above is Newtorı's law ofviscosity.

Materials other than fluids cannot satisfy the definition ofa fluid. A plastic substance will deform a certain amount proportional to the force, but not continuously when the stress applied is below its yield shear stress. A complete vacuum between the plates would cause deformation at an ever-increasing rate. If sandwete placed between the two plates, Coulomb friction would require a finite force to cause a coııtinuous motion. Hence, plastics and solids are excluded from the classification of fluids.

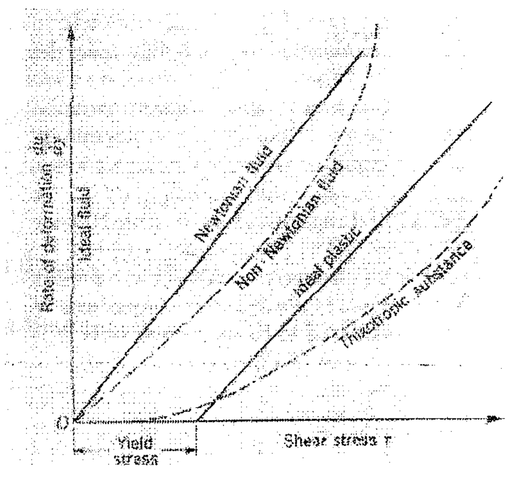


Figure.1.1. Rheological diagram

Fluids may be classified as Newtonian or non-Newtonian. In Newtonian fluid there is a linear relation between the magnitudes of.appiied shear stress and the resulting rate of deformation (μ constant), as shown in Fig. 1.1. In non-Newtonian fluid there is a nonlinear relation between the magnitude of applied shear stress and the rate of angular deformation. An ideal plastic has a definite yield stress and a constant linear relation of ı- to *dul* dy. A thixotropic substance, such as printer's ink, hasa viscosity that is dependent upon the immediately prior angular deformation of the substance and has a tendency to take a set when at rest. Gases and thin liquids tend to be Newtonian fluids, while thick, long-chained hydrocarbons may be non-Newtonian.

For purposes of analysis, the assumption is frequently made that a fluid is non-viscous. With zero viscosity the shear stress is always zero, regardless of the motion of the fluid, lithe fluid is also .considered to be incompressible, it is then called an ideal fluid.

1.2 PROPERTIESOF FLUID

Density

The density p ofa fluid is de:fined as its mass per unit volume. To define density ata point, the mass Am of fluid in a small volume AV surrounding the point is divided by AV and the limit is taken as AV which can be expressed as follow;

$$p= \lim \frac{Sm}{AV}$$

Specific volume

The specific volume v_s is the reciprocal ofthe density p;that is, it is the volume occupied by unit mass of fluid, where it can be expressed as follow;

$$v_s - \frac{1}{p}$$

Unit gravjty force

The unit gravity force, .y,is the, force of gravity per.unit .volume. Itchangeswith Iocation, depending upon gravity.

$$\gamma = pg$$

Pressure

The normal force pushing against a plane area divided by the area is the average pressure. The pressure at a point is the ratio of normal force to area as the area approaches a small value enclosing the point. If a fluid exerts a pressure against the walls ofa container, the container will exert a reaction on the fluid which will be compressive, Liquids can sustain very high compressive pressures, but unless they are extremely pure, they are very weak in tensi on. It is for this reason that the absolute pressures used are never negative, since this would imply that fluid is sustaining a tensile stress. Pressure p has the units force per area, which is Newton per square meter, called Pascal (Pa). Pressure may also be expressed in terms of an equivalent height h ofa fluid column as it is indicated below;

$$p=yh.$$

Absolute pressure is symbolized by P, while gage pressures are indicated by p.

Viscosity

The viscosity ofa fluid is a measure of its resistance to shear or angular deformation. For example the motor oil has a high viscosity; on the other hand gasoline has a low one. Of all the fluid properties, viscosity requires the greatestcotı.sideratiôfi i!ltthatstıidy ôf flüid' flow.

The viscosity of a gas increases with temperature, but the viscosity of liquid decreases with temperature: The variation in temperature trends can be explained by examining the causes of viscosity. The resistance ofa fluid to shear depends upon itscohesıon and upon its rate of transfer of molecular momentum. A liquid, with molecules much more closely spaced than a gas, has cohesive forces much larger than a gas. Cohesion appears to be the predominant cause of viscosity in a liquid; and since cohesion decreases with temperature the viscosity does likewise. A gas, on the other hand, has very small cohesive forces. Most ofits resistatlcetôshea.fstress·is the result ofthe transfer ofınolecularrrıomentum.

Molecular activity gives rise to an apparentshear stressin gases which is more important than the cohesive forces, and since molecular activity increases with temperature, the viscosity ofa gas also increases with temperature. For ordinary pressures viscosity is independent of pressure and depends upon temperature only. For very great pressures, gases and most liquids have shown erratic variations of viscosity with pressure.

A fluid at rest or in motion so that no layer moves relative to an adjacent layer will not have apparent shear forces set up, regardless of the viscosity, because du/dy is zero throughout the fluid..Hence, in the study of fluid statics, no shear forces can be considered because they do not occur in a static fluid, and the only stresses remaining are normal stresses, or pressures. This greatly simplifies the study of fluid static, since any free body of fluid can have only gravity forces and normal surface forces acting on it.
The dimensions of viscosity are determined from Newtorı's law of viscosity. Solving for the viscosity μ;

$$\mu = \frac{t:}{du/dy}$$

The SI unit of viscosity which is the Pascal second (symbol Pa) has no name.

Kinematics Viscosity

The viscosity μ is frequently referredto as the absolute viscosity or the dynamic viscosity to avoid confusing it with the kinematics viscosity.v, which-isttheratio ofviscosity to mass density:

$$v = \frac{\mu}{p}$$

The kinematio viscosity occurs in many applications, e.g., in the dimensiorılessReynolds rıı.ımber' for motion of a body through a fluid, Vl/v, in which V is the body velocity and l is a representative linear measure of the body size. The dimensions of v are L^2T^{-1}. The SI unit of kinematics viscosity is 1 m^2/s, and it has no name.
Viscosity is practically independent of pressure and depends upon temperature only. The kinematic viscosity of liquids, and of gases at a given pressure, is substantially a function of temperature.

Continuum

In dealing with fluid-flow relations on a mathematical or analytical basis, it is necessary to consider that the actual molecular structure is replaced by a hypothetical continuous medium, called the continuum. For example, velocity at a point in space is indefinite in a molecular medium, as it would be zero at all times except when a molecule occupied this exact point, and then it would be the velocity of the molecule and not the mean mass velocity of the particies in the neighborhood. This dilemma is avoided if one considers velocity at a point to be the average or mass velocity of all molecules surrounding the point, say, within a small sphere with radius large compared with the mean distance between molecules. With n molecules per cubic centimeter, the mean distance between molecules is of the order $n^{-1/3}$ cm. Molecular theory, however, must be used to calculate fluid properties (e.g., viscosity) which are associated with molecular motions, hut continuum equations can be employed with the results of molecular calculations.

The quantities density, specific volume, pressure, velocity, and acceleration are assumed to vary continuously throughout a fluid (or be constant).

1.3 CONCLUSION

The discussion of this chapter is about fluid. At the beginning a brief about the fluid its definition, then about the properties that affect the fluid like the viscosity, continuum, density, specific volume, unit gravity force and the pressure.

CHAPTERII
FLUID-FLOW CONCEPTSAN0
BASIC EQUATIONS

The statics of fluids is almost an exact science, unit gravity force (or density) being the only quantity that must be determined experimentally. On the other hand, the nature of flow ofa real fluid is very complex. Since the basic laws describing the complete motion ofa fluid are not easily formulated and handled mathematically, recourse to experimentation is required.

2.1 FLOW CHARACTERISTICS; DEFINITIONS

Flow may be classified in many ways such as turbulent, laminar; real, ideal; reversible, irreversible; steady, unsteady; uniform, non-uniform; rotational, irrotational. in this and the following section various types of flow are distinguished.

Turbulent flow situations are most prevaletıt-in engineering practice, in turbulent flow the fluid particles move in very irregular baths; causirığ an excharrge ofemonientum from one portion of the fluid to another in a manner somewhat'similanto the molecular.momentum transfer but ona much larger scale. The fluid particles can range in size from very small to very large. in a sitııation in which the flow could be either turbulent or non-turbulent (laminar), the turbulence sets "tıp greater shear stresses throughout the fluid and caıısesmore irreversibility or losses.

In laminar flow, fluid particles move along smooth paths in laminas, or layers, with one layer gliding smoothly over an adjacent layer. Laminar flow is governed by Newton's law of viscosity or extensions of it to three-dimensional flow, which relates shear stress to rate of angular deformation. in laminar flow, the action of viscosity damps out turbulent .tendencies, Laminar flow is not stable in situations involving combinations of low viscosity, high velocity, or large flow passages and breaks down into turbulent flow.

An equation similar in form to Newton's law of viscosityrrfay be written for turbulent flow as follow:

$$t = \eta \frac{du}{dy}$$

where the factor, η, is called the eddy viscosity which depends upon the fluid motion and the density.

An ideal fluid is frictionless and incompressible and should not be confused with a perfect gas. The assumption of an ideal fluid is helpful in analyzing flow situations involving large expanses of fluids, as in thernotion of an airplane ora submarine. A frictionless fl.uid is nonviscous, and its fl.owprocesses are reversible. The layer of fluid in the immediate neighborhood of an actual flow boundary that has had its velocity relative to the boundary affected by viscous shear is called the boundary layer. Boundary layers may be laminar or turbulent, depending generally upon their length, the viscosity, the velocity of'the flow near them, and the boundary roughness.

Adiabatic flow is that flow of a fluid \in whi.ch no heat is transferred to. or from:.the fluid, Reversible adiabatic flow is called isentropic/flow. To proceed in an orderly manner into the analysis of fluid flow requires a clear understanding of the terminology involved. Several of the more important technical terms are defined and illustrated in this section. Steady flow occurs when conditions at any point in the fluid do not change with the time; This can be expressed as $\partial v / \partial t = 0$, in which space (x, y, z coordinates of the point) is held constant. Likewise.in steady flow there is no change in density p, pressure p or temperature T with time at any point.

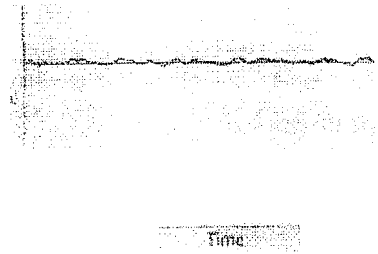


Fig2.1 .velocity ata point inSteady<fü:rbulerflow

In turbulent flow, owing to the erratic motion of the fluid particles, there are always small fluctuations occurring at any point. The definition for steady flow must be generalized somewhat to provide for these fluctuations. To illustrate this, a plot of velocity against time, at some point in turbulent flow, is given in Fig. 2.1. When the temporal mean velocity

$$v_1 = \int_0 v\,dt$$

Indicated in the figure by the horizontal line, does not change with the time, tin flow is said to be steady. The same generalizatiôrta.pplies to density, pressure, temperature, ete., when they are substituted for v in the abôve fôrınula.

The flow is unstea.cly whenbôfrditions at any point change with the time, $av / at * 0$. Water being pumped through"a fi:xed•sysfömat a constant rate is an example of steady flow. Water being pumped through afıxeclsystem/atan increasing rate is an example ofunsteady flow.

Uniform flow ôcföu:fs wheH, atevery point, the velocity vector is identically the same (in magnitude and clireCtiôn)<fotafrygiven instant. In equation form, $av! as = 0$, in which time is held constant and 6/is a>füsplacement in any direction. The equation states that there is no change in the velocity vector in any direction throughout the fluid at any one instant. It says nothing about the charıg~Ul velocity at a point with time. in flow of a real fluid in an open or closed conduit, the de-firtitibtbf uniform flow may also be extended in most cases even though the velocity vector 'at'tli~"b6fuidaı:yS always zero. When all parallel cross sections through the conduit are identical a.rtdthe a.verage velocity at each cross section is the same at any given instant, the flow is said"töb~ttrtiform.

Flow such that the velocity vector varies from place to place at any instant ($av / as * 0$) is nonuniform flow. A liquid beirıgpumped through a long straight pipe has uniform flow. A liquid flowing through a reducing sectiôn or through a curved pipe has nonuniform flow. Examples of steady and unsteady flow and of uniform and nonuniform flow are liquid flow through a long pipe ata constant rate is steady uniform flow; liquid flow through a long pipe ata decreasing rate is unsteady uniform flow; flow through an expanding tube at a constant rate is steady nonuniform flow; and flow thr~xpanding tube at an increasing rate is unsteady nonuniform flow. Rotation ofa fluid partide about a given axis, say the z axis, is defined as the average angular velocity of two infinitesimal line elements in the particle that are at right angles to each other and to the given axis. If the fluid particles within a region have rotation about any axis, the flow is called rotational flow, or vortex flow. If the fluid within a region has no rotation, the flow is called irrotational flow. it. is shown in texts on hydrodynamics that if a fluid is at rest and is frictionless, any later motion ofthis fluid will be irrotational.

One-dimensional flow negleots-variationsor changes in velocity, pressure, ete., transverse to the main flow direction. Conditions at a cross section are expressed in terms of average values of velocity, density, and. other properties. Flow through .a pipe, for example, may usually be characterized as one dimensional. Many practical problems can be handled by this method of analysis, which is mµchisimpler than two- and three-dimensional methods of analysis. In two-dimensional flow.allpa.tJ:iClesarc assumed to flow in parallel planes along identical paths in each of these planes; hence, t.lı~re are no changes in flow normal to these planes. The flow net is the most useful meth()<lifüf>a.nalysis of two-dimensional-flow situations. Three-dimensional flow is the most generahfle>}M(ig which the velocity components u, v, w in mutually perpendicular directions are functioıı.sgfspace coordinates and time x, y, z, and t. Methods of analysis are generally complex mathefüa.ticallyand only simple geometrical flow boundaries can be handled. In steady flow, since Jlı~.re is no change in direction of the velocity vector any point, the streamline hasa fixed iıiclirtationat every point and is, therefore fixed in space. A particle always moves .tangent to the-streamline; hence, in stead.flow the patlı .Qf ◁. particleis a streamline, lı-ı unsteady flow, sincethedirection of the velocity vector at any point may change with time, a streamline may shi:ft/is spade from instant to instant. A partide then follows one streamline one instant another one theirtextinstant, and so on, so that the patlı of the particle may have no resemblance to any given.itista.ııtarteoustreamline.

A dye or smoke is frequentlyihjected into a fluid in order to trace its subsequent motion. The resulting dye or smoke trails are balled streak lines. In steady flow a streak line is a streamline and the patlı ofa particle.

Streamlines ın two-dimensional flow can be obtained by inserting fıne, bright particles (aluminium dust) into the fluid, brilliantly lighting one plane, and taking a photograph of the streaks made in a short time interval. Tracing on the picture continuous lines that have the direction of the streaks at every pointportrays the streamlines for either steady or unsteady flow.

In illustration of an incompressible two-dimensional flow, the streamlines are drawn so that, per unit time, the volume flowirıgibetween adjacent streamlines is the same if unit depth is considered normal to the planeiöfthe figure. Hence, when the streamlines are closer together, the velocity must be greater, and Viceversa. If v is the average velocity between two adjacent streamlines at some positionwhetethey are h apart, the flow rate Aq is

$$Sq=vh$$

At any other pösitidllôrtXfüe chart where the distance between streamlines is h_1, the average velocity is v_1 = Aq/h_1.B§iô.creasing the number of streamlines drawn, i.e., by decreasing Aq, in the limiting case thevetôdHy afa point is obtained.

A stream tube is th@ttı.b~mı:i'cle by all the streamlines passing through a small, closed curve. In steady flow it is fixecttrı>space and can have no flow through its walls because the velocity vector has no component nörtl1a.Fto the tube surface.

2.2 DIMENSIONAI.1.ANALYSIS AND DYNAMIC SIMILITUDE

Dimensionless paratıJ.~~~i~)-~igrıifica,ntly. deepen our understanding. of fluid-flow phenomena in a way which is analogoı.ı,şiJo Jhe case of a hydraulic jack, where the ratio of piston diameters determines the mecfı~~i?il/adyantage, a dimensionless number which is independent of the overall size of the jack./They permit limited experimental results to be applied to situations involving different physipfü <:limensions and often different fluid properties. The concepts of dimensional analysis intrödğc::~djn this chapter plus an understanding of the mechanics of the type of flow under study l'tlı:tg~ ipossible this generalization of experimental <lata. The consequence of such generali~ti9rı js manifold, since one is now able to describe the phenomenon in its entirety and is Jt()frestricted to discussing the specialized experiment that was performed. Thus, it is possible to çorıduct fewer, although highly selective, experiments to

uncover the hidden facets of the problem and thereby achieve important savings in time and money. The results of an investigation can also be presented to other engineers and scientists in a more compact and meaningful way to facilitate their use. Equally important is the fact that, through such incisive and uncluttered presentations of information, researchers are able to discover new features and missing areas of knowledge of the problem at hand. This directed 'advancement of our understanding of a phenomenon would be impaired if the tools of dimensional analysis were not available. in the following chapter, dealing primarily with viscous effects, one parameter is highly significant, viz., the Reynolds number, dealing with compressible flow, the Mach number is the most important dimensionless parameter, dealing with open channels, and the Froude number has the greatest significance.

Many of the dimensiônless parameters may be viewed as a ratio of a pair of fluid forces, the relative magnitude jndicating the relative importance of one of the forces with respect to the other. If some forces in a particular flow situation are very much larger than a few others, it is often possible to neglecf.füe effect of the smaller forces and treat the phenomenon as though it were completely dytyrpıined by the major forces. This means that simpler, although not necessarily easy, rrıathe:triaticaland experimental procedures can be used to solve the problem.

2.2.1 DIMENSIONALHOMOGENEITY AND DIMENSIONLESS RATIOS

Solving practical desigti problems in fluid mechanics usually requires both theoretical developments and experirtıental results. By grouping significant quantities into dimensionless parameters, it is possibletô reduce the number of variables appearing and to make this compact result (equations or data plôts) applicable to all similar situations.

If one were to write the eqtiation öf motion l: F = ma for a fluid particle, including all types of force terms that could act, stichas gravity, pressure, viscous, elastic, and surface-tension forces, an equation of the sum of these förces equated to ma, the inertial force, would result. As with all physical equations, each term :triusthave the same dimensions, in this case, force. The division of each term of the equation by any ô11e of the terms would make the equation dimensionless. For example, dividing through by the inertial force term would yield a sum of dimensionless parameters equated to unity. The relative size of any one parameter, cornpared with unity, would indicate its importance. If one were to divide the force equation through by a different term, say the viscous force term, another set of dimensionless parameters would result. Without experience in the flow case it is difficult to determine which parameters will be most useful.

2.3 DISCUSSION<OF DIMENSIONLESS PARAMETERS

The four dimensionless >paraırietefs -Reynolds number, Froude number, Weber nurnber, and Mach number- are bf iırip6filince in correlating experimental data. They are discussed in this section, with partic:tılaf eıriphasis placed on the relation of pressure coefficient to the other pararneters.

The Reynolds Number

The Reynolds numberVDp/μ is the ratio of inertial forces to viscous forces. A critical Reynolds number distinguishes'am.Ông flow regirnes, SUCh as laminar Of turbulent flow in pipes, in the boundary layer, or afoüıid irnmersed objects. The particular value depends upon the situation. In cornpressible flow, thel\1:ach number is generally more significant than the Reynolds number,

The Froude Numben

The Froude number-V/t ‹, when squared and then multiplied and divided by pA, is a ratio of dynamic (of inertial)fötC~tôWeight. With free liquid-surface flow the natıre of the flow (rapid or tranquil) depends uporı whether the Froude number is greater Of less than unity. it is useful in calculations of hydta.ü.litjü.mp in design of hydraulic structures, and in ship design.

TheWeber **Number**

The Weber number V21p/8-Vısthe:ratio of inertial forces to surface-tension forces (evident when numerator and denomi1 1at()fa,:tdllUltİplied by 1). it is İmportant at gas-liquid Of liquid-liquid interfaces and also whefetheseiriterfaces are in contact with a boundary. Surface tension causes small (capillary) waves and dfopletformation and has an effect on discharge of orifices and weirs at very small heads. The effect of sıirface tension on wave propagation is shown in Fig. 4.1. To the left of the curve's minimum thewave speed is controlled by surface tension (the waves arc called ripples), and to the right ofthe curve's minimum gravity effects are dominant.

The Mach Number

The speed of sound in a liquid is written $\sqrt{K/p}$ if K is the bulk modulus of elasticity Of $c = \sqrt{KRT}$ (k is the specific heat ratio and T the absolute temperature for a perfect gas). V/c Of $V/\sqrt{K/p}$ is the M:~6h number. It is a measure of the ratio of inertia forces to elastic forces. By squaring V/c and multiplying by $pA/2$ in numerator and denominator, the numerator is the dynamic force and the denominator is the dynamic force at sonic flow. It may also be shown to be a measure of the ratio of kinetic energy of the flow to intemal energy of the fluid; it is the most important correlating parameter when velocities are near Of above local sonic velocities.

2.4 CONCLUSION

In this chaptef.w"~iıtroduced the flow oharacteristics, its definitions and its mean classifications. We discussed thfg~h~falform of Newton's viscosity law. Anda brief explanation on how the dimensionless pararnetets significantly deepen our understanding of fluid-flow phenomena. Many of the dimefrsiqrtless parameters may be viewed as a ratio of a pair of fluid forces, the relative magnitudeiııdicating the relative importance of one of the forces with respect to the other.

We showed thatsôl~trigipractical design problems influid mechanics usually requires both theoretical developments< atıd. experimental results. By grouping significant quantities into dimensionless parameters,\and how it is possible to reduce the number ofvariables appearing and to make this compactreştılt(equations of data plots) applicable to all similar situations. Without forgetting about the foı.ırdimensionless parameters, Reynolds number, Froude number, Weber number, and Mach nurnber,

CHAPTERIII

VISCOUS FLOW iN PIPES

In this chapter we will apply the basic principles *to* a specifrc, important topic-the flow of viscous, incompressible fluids in pipes and ducts. The transport ofa fluid in a closed conduit commonly called a pipe if it is of round cross section or a clue if it is not round, is extremely important in our daily operations. A brief consideration of the world around us will indicate that there is a wide variety of applications of pipe low. Such applications range from the large, man-made Alaskan pipeline that carries crude oil almost 800 miles across Alaska, to the more complex natural systems of pipes that carry blood throughout our body and air into and out of our lungs. Other ex'atnples include the water pipes in our homes and the distribution system that delivers the waterfrom the city well to the house. Numerous hoses and pipes carry hydraulic fluid or other fluidsfo various components of vehicles and machines. The air quality within our buildings is mainta.ıııedat comfortable levels by the distribution of conditioned air through a maze of pipes and .ducts, Although all of these systems are different, the fluid-mechanics principles goverıııngtl:J.ɇfluid motions are common. The purpose of this chapter is to understand the basic procesSesitıvölved in such flows.

Some of the basic cofüponents ofa typical pipe system are shown in Fig. 3.1. They include the pipes themselves, the various fittings used to connect the individual pipes to form the desired system, the flow rate control devices, and the pumps or turbines that add energy to or remove energy from the flµid. Even the most simple pipe systems are actually -quite complex when they are viewed in terms ()frigorous analytical considerations. We will use an exact analysis of the simplest pipe flowtôpics .sµch as laminar flow in long, straight, constant diameter pipes and dimensional analysis corışiderations combined with experimental results for the other pipe flow topics. Such an approach js not unusual in fluid mechanics investigations. When real world effects are important such as viscous effects in pipe flows, it is often difficult or impossible to use only theoretical method to obtain the desired results. A judicious combination of experimental <lata with theoretical considerations and dimensional analysis often provides the desired results.

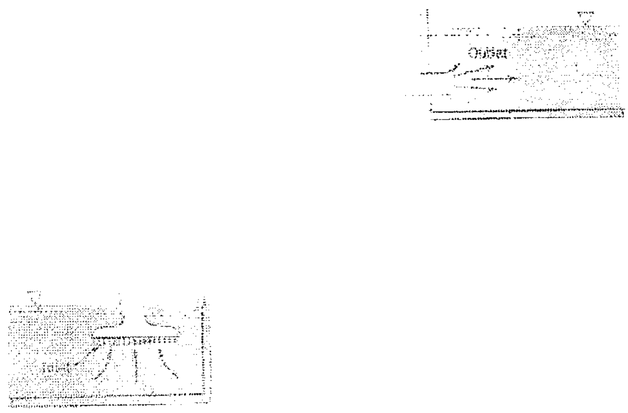


Figure 3.1. Typical pipe system component.

3.1 GENEAAI..JCHARACTERISTICS OF PIPE FLOW

Not all conduits used *to* transport fluid from one location *to* another are round *in* cross section, mest of the coıtıııtıôri.Ones are. These include typical water pipes, hydraulic hoses, and other conduits that are c:İe§ıgrıed to withstand a considerable pressure difference across their walls without undue distôrtion of their shape. Typical conduits of noncircular cross section include heating and a.if Côrıditiöning ducts that are eften of rectangular cross section. Normally the pressure differerıce between the inside and outside of these ducts is relatively small. Mest of the basic principles involved are independent of the cross-sectional shape, although the details of the flow may be depe:rıderıt on it. Unless otherwise specified, we will assume that the conduit is round, although wewiffshow how to account for other shapes.

We assume that the/pipeis completely filled with the fluid being transported. Thus, we will not consider a concrete pipethrough which rainwater flows without completely fılling the pipe. Such flows called open-ch~ı:ı~eLflôw. The difference between open-channel flow and the pipe flow of this chapter is in the furida.lnerıtal mechanism that drives the flow. For open-channel flow, gravity alone is the driving force ..the water flows.

3.1.1 LAMIN AR AND TURBULENT FLOW

The flow ofa fluid in a pipe may be laminar flow or it may be turbulent flow. Osbome Reynolds (1842-1912). A British Scientist and mathematician, was the 1st to distinguish the difference between these two classifications of flow by using a sirnple apparatus. 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. 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. Fora 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. The curves shown in Figure 3.2, represent the x component of the velocity' as function of time, at a point A in the flow. The random fluctuations of the turbulent flow are what disperse the dye throughout the pipe and cause the blurred appearance. For laminar flow in a pipe there is only one component of velocity, V = ui. For turbulent flow the predominant component of velocity is also along the pipe. But it is unsteady and accompanied by random components normal to the pipe axis, V= ui + uj + wk. Such motion in a typical flow occurs too last for our eyes to follow. Slow motion pictures of the flowcan more clearly reveal the irregular, random, turbulent nature ofthe flow.

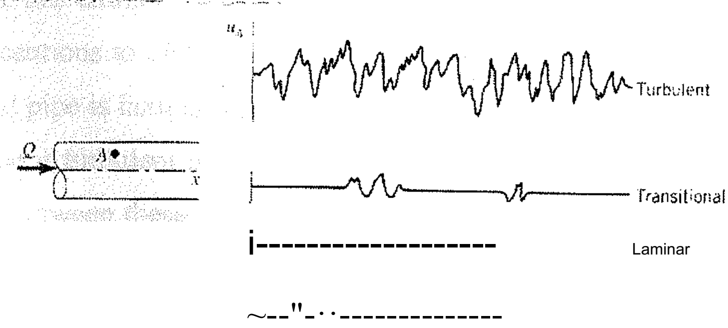


Figure 3.2. Time dependence of fluid velocity ata point

We should not label dimensional quantities as being large or small, such as "small enough flow rates' in the preceding paragraphs. Rather, the appropriate dimensionless quantity should be identified and the small or large character attached to it. A quantity is large or small only if relative to a reference quantity. The ratio of those quantities results in a dimensionless quantity, for pipe flow the most important dimensionless parameter is the Reynolds number, Re-the ratio of the inertia to viscous effects in the flow. Reynolds number is shown as;

$$Re=pVD/g.$$

Where V is the average\velocity in the pipe, should replace the term flow rate. That is, the flow in a pipe is laminar,)trarisitional, or turbulent provided the Reynolds number is small enough, intermediate, or 'large eriough. it is not only the fluid velocity that determines the character of the flow -its density, viscosity, and the pipe sizes are of equal importance. These parameters combine to produce the Reynolds number. The distinction between laminar and turbulent pipe how and its depe~~2~cton an appropriate dimensionless quantity was first pointed out by Osborne Reynoldsin1~83.

The Reynolds numberra.uges for which laminar, transitional, or turbulent pipe flows are 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 ofth€. entrance .region, and .the, .like, For general engineering .purposes.fi.e .., without undue precaufiôns to eliminate such disturbances), the following values are appropriate: The flow in a round pipe is .laminar if the Reynolds number is less than approximately 2100. The flow in a round pipe is'nirbiilent ifthe Reynolds number is greater than approximately 4000. For Reynolds numbers between these two limits, the flow may switch between laminar and turbulent conditions in an apparently random fashion (transitional flow).

3.1.2 ENTRANCE REGION AND FULL Y DEVELOPED FLOW

Any fluid flowing in a pipe had to enter the pipe at some location. The region of flow near where the fluid enters the pipe is termed the entrance region. It may be the first few feet of a pipe connected to a tank or the initial portion ofa long run ofa hot air duct corning form a fumace.

As is shown in Figure 3.3, the fluid typically enters the pipe with a nearly uniform velocity profile at section (I). As the fluid moves through the pipe, viscous effects cause it to stick to the pipe wall (the no-slipboundary condition). This is true whether the fluid is relatively in viscid air or very viscous ôil. Thus, a boundary layer in which viscous effects are important is produced along the pipe wall.ş).ı9hJhat the initial velocity profile changes with distance along the pipe, x. until the fluid feıı̧çh~.tj:ıe end of the entrance length, section (2), beyond which the velocity profile does not varyy;ifh .x. the boundary layer has grown in thickness.

Viscous effects are of considerable importance within the boundary layer. For fluid outside the boundary layer [within the in-viscid core surrounding the centerline from (1) to (2)], viscous effects are negligible. The shape of the velocity profile in the pipe depends on whether the flow is laminar or turbulent, as does the length of the entrance region Le. As with many other properties of pipe flow, the dimensionless entrance length Ls/D. correlates quite well with the Reynolds number, typical entrance lertgths are given by;

$$Le/D \approx 0.06\,Re \text{ for laminar flow}$$

and

$$Le/D = 4.4\,(Re)^{1/6} \text{ for turbulent flow}$$

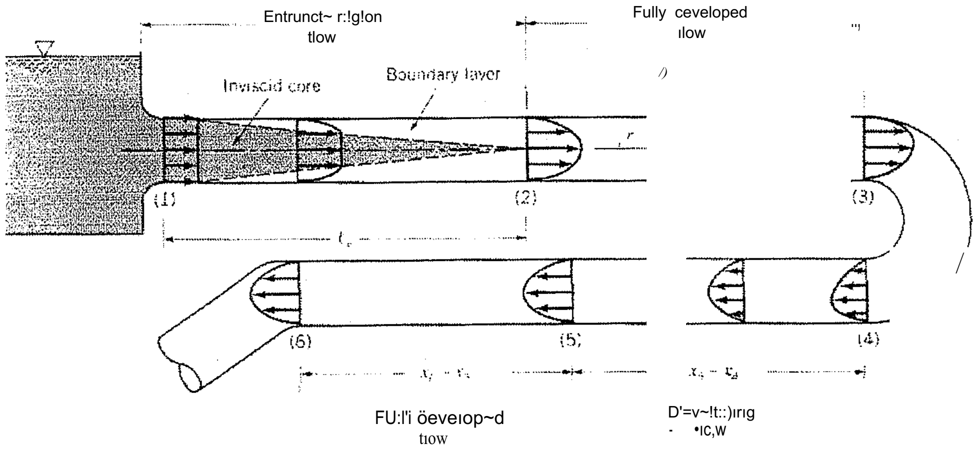


Figure3.3 Entrance region, developing flow and fully developed in the pipe.

For very low Rey:nôldstıtimbers flows the entrance length can be quite short (Le= 0.6D ifRe = 10), whereasforla.rgeRey:nolds number flows it may take a length equal to many pipe diameters before the end ofth.eentrance region is reached (Le =120D for Re= 200). For many practical engineering problertis, to<Re<l 0^5 so that 20D< Le <30D.

Calculation of th~\relÇ>cityprofile and pressure distribution within the entrance region is quite complex. Howevet,()ı:ıce the fluid reaches the end of the entrance region, section (2) of figure 3.3, the flow is siın.plE:t.to describe because the velocity is a unetion of only the distance from the pipe centerline, r, arıdirıdependent ofx. This is true until the character ofthe pipe changes in some way, such asa cfüırığe in diameter, or the fluid flows through a bend, valve, or some other ·compönerit at sectiôff(:3).ThefröWbetweerı (2}and·(3)is·termedfully·developed; Beyondthe in interruption ofthe fullydeveloped flow [at section (4)], the flow gradually begins its retum to its fully developed chara.ctei.[sedion (5)] and continues with this profile until the next pipe system component is reached [section (6)]. In many cases the pipe is long enough so that there is a considerable length of full)'developed flow compared with the developing flow length [(x3-x2)>> le and (x6-xs)>>(xs..x4)]. In other cases the distances between one component ofthe pipe system and the next comporietıt is so short that fully developed flow is never achieved.

3.1.3 PRESSURE AND SHEAR STRESS

Fully developed steady flow in a constant diameter pipe may be driven by gravity and/or pressure forces. For horizontal pipe flow, gravity has no effect except fora hydrostatic pressure variation across the pipe, yD that is usually negligible. It is the pressure difference, Ap=pt-pa, between one section of the horizontal pipe and another which forces the fluid through the pipe. Viscous effects provide the restraining force that exactly balances the pressure force, thereby 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 ofa pipe, the fluid accelerates or decelerates as it flows, the velocity profile changes from a uniform profile at the entrance of the pipe to its fully developed profile at the end of the entrance region. Thus, in the entrance region there is a balance between pressure, viscous, and inertia forces. The result is pressure distribution alone the horizontal pipe as shown in Fig 3.4. The magnitude of the pressure gradient, dp/dx, is larger in the entrance region than in the fully developed region.

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.

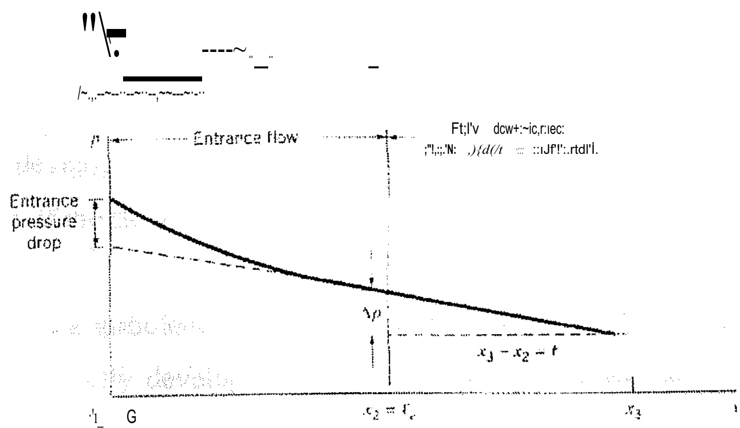


Figure 3.4 Pressure distributions along the horizontal pipe

In terms of a force balance, the pressure force is needed to overcome the viscous forces generated. In terms of an energy balance, the work done by the pressure force is needed to overcome the viscous dissipation of energy throughout the fluid. 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 laminar flow is a direct result of momentum transfer among the randomly moving molecules. The shear stress in turbulent flow is largely a result of momentum transfer among the randomly moving, finite-sized bundles of fluid particles. The net -result is that the physical properties ofthe shear stress are quite different for laminar flow than for turbulent flow.

3.2 FULLYDEVELOPED LAMINAR FLOW

As is indicated iri the previous Sec::tion, the flow irilong, stfaight, constant diameter sections ofa pipe becomes fully develôped.th'atis,tKevelöcityipfo:fileis the same at any cross section ofthe pipe. Although this is true whether the flôw<is laminaf'ôf ifüfüulent, the details of the velocity profile are quite different for these two ıypes of flôw. Kiıôwledge of the velocity profile can lead directly to other useful information such as pressure drop, head loss, flow-rate, and the like. Thus, ~ve begin by developing the equation for the velocity profile iri fıılly develöped laminaLflow.. If ... the flow is not fully developed, a theoretical analysis becomes much more complex and is outside the scope ofthis text. Ifthe flow is turbulent, a rigorous theoreticalanalysis is a.syettıotpôssible.

Although most flows are turbulent rather than laminar, and many pipes are not Iong enough to allow the attainment of fully developed flow, a theoretical treatment a.nd full understanding of fully developed laminar flow is of considetable irrıporta.tıce.< First/itreptesents one of the few theoretical viscous analyses that can be carried out exactly without using other ad hoc assumptions or approximations. An understa.nding of the method of analysis and the results obtained provides a foundation from which to carry out more complicated analyses. Second, there

are many practical situations involving the use of fully developed laminar pipe flow.
There are numerous ways to derive important results pertaining to fully developed laminar flow.
Three altematives include: .(1) from F = ma applied directly to a fluid element.
(2) From the Navier-Stokes equations of motion.
(3).From dimensional analysis methods.

3.2.1 ENERGYG0NS1DERATI0NS

In the previous three sections we derived the basic laminar flow results from application ofF = ma Or dimensionala.halysis Cônsiderations. lt is equally important to understand the implications of energy considerations.ofsuch flows. To this end we consider the energy equation for incompressible;rsteady flow between two locations as;

$$\frac{p_1}{\gamma}+\alpha_1\frac{V_1^2}{2g}+z_1=\frac{p_2}{\gamma}+\alpha_2\frac{V_2^2}{2g}+z_2+h_L$$

Recall that aıand&:i'.kinetic energy coefficient, and hı: head loss which accounts for any energy loss assôcıatec{Withthe flow. From the ideal inviscid cases, $\alpha_1=\alpha_2=1$, $h_L=0$, and the energy equatiôıiredtteedföthe familiar Bemoulli equation.
Even though the Velôcity profile in viscous pipe flow is not uniform, for fully developed flow it is not change from section 1 to 2 so that $\alpha_1=\alpha_2$. Then the energy equation becomes;

$$\left(\frac{p_1}{\gamma}+z_1\right)-\left(\frac{p_2}{\gamma}+z_2\right)=h_L$$

The energy dissipaiedbfthe viscous forces within the fluid is supplied by the excess work done by the pressure and ğravity.Then we can fi.nd out that the head loss can be written as follow;

$$h_L=\frac{4\,l\,\tau_w}{\gamma D}$$

It is the shear stress at the wıillwhich is related to the viscosity and the shear tress throughout the fluid that is responsible for theheadfoss.

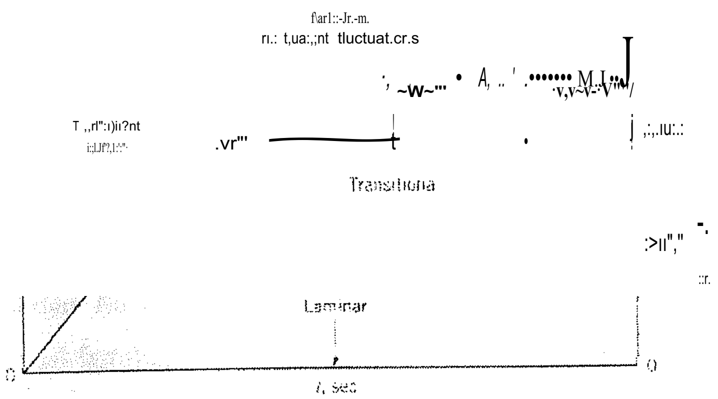
3.3 FULL Y DEVELOPED TURBULENT FLOW

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 ofbaffling aspects ofturbulence. Although a considerable amount of the knowledge about the topic has been developed, the field of turbulent flow still remains the least understöödarea of fluid mechanics.

3.3.1 TRANSITIONFROM LAMINAR TO TURBULENT FLOW

For any flow geometry; there is one or more dimensionless parameter such that with this parameter value b~lôwCa\patticular value the flow is laminar, whereas with the parameter value larger than a certaill!Y?.fü~ftheflow is turbulent. The important parameters involved as Reynolds number, Mach nurrıbefğn<:iôther dimensionless parameter, and their critical values depend on the specific flow sitµa.fü>11.ti11yôlved. For example, flow in a pipe and flow along a flat plate (boundary layer, tlôw) çğtı/be laminar or turbulent, depending on the value of the Reynolds number involy~q.:\1fôf/pipe flow the value of the Reynolds number twist is less than approximately 21QQfôrfüırrı.inarflow and greater than approximately 4000 for turbulent flow. For flow along a flat.plğt~ifli~)transition between laminar and turbulent flow occurs at a Reynolds number of approximaf~ly(~J)OOOO, where the length term in the Reynolds number is the distance measured from thelea<:iip.g>edgeofthe plate.

Consider a long secfrônôf pipe that is initially filled with fluid at rest. As the valve is operıed to start the flow, the flow.vvill.iticrease its velocity and, hence, The Reynolds number increase from zero to their maximurtıst~@ly.state flow values. Assume this transient process is slow enough so that unsteady effects are/rı~gligible. For an initial time period the Reynolds number is small enough for laminar floW1:öôt:cl.lrtAtsome time the Reynolds number reaches 2100, and the flow begins its transiti on to turbule11t;çônditions. Intermittent spots or bursts of turbulence appear. As the Reynolds number is increas.ed.the entire flow field becomes turbulent. The flow remains turbulent as long the Reynolds nµ.rrıberexceeds approximately 4000.



FigureJ.5Transitions from laminar to turbulent flow in a pipe

A typical trace of the axial comoonenr ofvelocity measured ata given location in the flow, u = u (t). Its irregular, random nature is the distinguishing feature of turbulent flow. The character of many ofthe important properties of the flow depends strongly on the existence and nature of the turbulent fluctuations or randomness indicated. The Reynolds number is infinite because the viscosity is zero, and the flow most surely would be turbulent. However, reasonable results were obtained by using the in-viscid Bemoulli equation as the governing equation. The reason that such simplified inviscid analyses gave reasonable results is that viscous effects were not very important and the velocity used in the calculations was actually the time-averaged velocity, u. Calculation of the heat transfer, pressure drop, and many other parameters would not be possible without inclusion of the seemingly small, but very important, effects associated with the randomness of the flow.

Consider flow in a pan of water placed on a stove. With the stove tumed off, the fluid is stationary. The initial sloshing has died out because of viscous dissipation within the water. With the stove tumed on, a temperature gradient in the vertical direction, (f) , is produced. The water temperature is [illegible] near the pan bottom and decreases toward the top of the fluid layer. if the temperature differences is very small the water will remain stationary, even though the water density is smallest near the bottorn of the pan because of the decrease in density with an increase in temperature. A further increase in the temperature gradient will cause buoyancy+-driven instability that results in motion-the light, warm water rises to the top, and the heavy cold water sinks to the bottorn. This slow, regular tuming over increases the heat transfer from the pan to the water and promotes mixing within the pan. As the temperature gradient increases still further, the fluid motion becomes more vigorous and eventually tums into a chaotic, random, turbulent flow with considerable mixing and greatly increased heat transfer rate. The flow has progressed from a stationary fluid to laminar flow, and finally to turbulent flow.

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. We are all familiar with the rolling, vigorous eddy type motion of the water in a pan being heated on the stove (even if it is not heated to boiling). Such finite sized random mixing is very effective in transporting energy and mass throughout the flow field, thereby increasing the various .rate processes involved. Laminar flow, on the other hand, can he thought of as very small but finite sized fluid particles flowing smoothly in layers, one over another. The only randomness and rnixingtake 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 (such as in the Cooling coils of an air conditioner or a boiler ofa power plant) would require an enormously large heat exchanger if the flow were laminar. Similarly, the required mass transfer of a liquid state to' a vapôr state (such as is needed in the evaporated cooling system associated with sweating) would require very large surfaces if the fluid flowing past the surfac13.wereJamirıar rather than turbulent,

Turbulence is also of importance in tile mixing of fluids. Smoke from a stack would continue for mil es asa ribbort ofpôllutanfwithout rapid dispersion within the surrounding air if the flow were laminar rather than furbulen.t Under certain atmospheric conditions this is observed to occur. Although there is mixin.g ôri a môlecular scale (laminar flow), it is several orders of magnitude slower and less effective tb.afı i:1:ieiri:ıixing on a macroscopic scale (turbulent flow). It is considerably easier to mix creaminfô;a cupôf coffee (turbulent flow) than to thoroughly mix two colors ofa viscous paint (laminar flôw).

In other situations laminar (rather than turbulent) flow is desirable. The pressure drop in pipes (hence, the power requirements for pumping) 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. The aerodynamic drag on an airplane wing can be considerably smaller with laminar.flow past it.than with turbulent flow.

3.3.2 TURBULENT SHEAR STRESS

The fundamental difference between laminar and turbulent flow lies in the chaotic, random behavior of the various fluid parameters. Such variations occur in the three components of velocity, the pressure, the shear stress, the temperature, and any other variable that has a held description. Turbulent flow is characterized by random, three dimensional vortices. Such flows can be described in terms of their mean values which are denoted with an over bar on which are superimposed the fluctuations which is denoted with a prime. Thus, if u = u (x, y, z, t) is the x component of instantaneous velocity, then its time mean or time average value, u, is expressed as follow;

$$u = \frac{u}{u^*} \cdot \int_{lo}^{to+T} u(x,y,z,t)\,dt$$

where the time interval, T, is considerably longerthan. the period of the longest fluctuations. considerably shorter than any unsteadiness of the average velocity. Since the square or a fluctuation quantity cannot be negative [(u)2 ?: 0], its average value is positive. On the other hand, it may be that the average of products of the fluctuations, such as u'v' are zero or nonzero.

The structure and characteristics of turbulence may vary from one flow situation to another. For example, the turbulence intensity or the level of the turbulence may be larger in a very gusty wind than it is in a relatively steady wind. The turbulence Intensity, φ, is often defied as the square root of the mean square of the fluctuating velocity divided by the time-averaged velocity. The larger the turbulence intensity the larger the fluctuations of the velocity. Well-designed wind tunnels have typical values of φ =0.01. although with extreme care values as low as φ = 0.0002 have been obtained, On the other hand, values of $\varphi \geq 0.1$ are found for the flow in the atmosphere and rivers. Another turbulence parameter that is different from one flow situation to another is the period of the fluctuations-the time scale of the fluctuations in many flows, such as the flow of water from a faucet, typical frequencies are on the order of 10, 100, or 1000 cycles per second (cps). For other flows, such. as. the Gulf Stream current in the Atlantic Ocean or flow of the atmosphere of Jupiter, characteristic random oscillations may have a period on the order ofhours, days, or more.

it is tempting to extend the concept of viscous shear stress for laminar flow ($\tau = \mu .du/dy$) to that of turbulent flow by replacing.u, .the instantaneous velocity, by u, the time averaged velocity. However, numerous .an<:l/.theoreticalstudies have shown that such an approach leads to completely incorrect results. That is, $\tau \neq \mu\, du/dy$. A physical explanation for this behavior can be found in the concept of what produces a shear stress.

Laminar flow is modeled as fluid particles that flow smoothly along in layers, gliding past the slightly slower or faster ones on either side. As is discussed in chapter 1, the fluid actually consists of numerous molecules darting about in an almost random fashion. the motion is not entirely random -a slight bias in one direction produces the flowrate we associate with the motion of fluid particles, u, As the molecules dart across a given plane (plane A-A. for example), the ones moving upward have come from an area of smaller average x component of velocity than the ones moving downward, which have come from an area of larger velocity.

The momentum flux in the x direction across.plane A - A, gives riseto adrag of the lower fluid_ on the upper fluid and an equal but opposite effect of die tipper fluid on the lower fluid. The sluggish molecules moving upward across plane A-A must be accelerated by the fluid above this plane. The rate of change of momentum in this process produces a shear force. Similarly, the more energetic molecules moving down across plane A - A must be slowed down by the fluid below that plane. This shear force is present only if there is a gradient in u = u(y), otherwise the average x component of velocity and momentum of the upward and downward molecules is exactly the same. In addition, there are attractive forces between molecules. By combing these effects we obtain the well-known Newton viscosity law: $\tau = \mu\, du/dy$, where on a molecular basis μ in related to the mass and speed and temperature ofthe random motion ofthe molecules.

Although the above random motion of the molecules is also present in turbulent flow, there is another factor that is generally more important. A simplistic way of thinking about turbulent flow is to consider it as consisting ofa series of random, three-dimensional eddy type motions as is depicted (in one dimension only), these eddies range in size from very small diameter (on the order of the size ofa fluid parti ele) to fairly large diameter (on the order of the size of the object or flow geometry considered). They move about randomly, conveying mass with an average velocity, u =u(y).This eddy structure greatly promotes mixing within the fluid. It also greatly increases the transport of x momentum across plane A-A. That is, finite parcels of fluid (not merely individual molecules as in laminar flow) are randomly transported across this plane, resulting in a relatively large (when compared with laminar flow) shear force.

The random velocity components that account for this momentum transfer (hence, the shear force) are u (for the x component of velocity) and u (for the rate of mass transfer crossing the plane). A more detailed consideration ofthe processes involved will show that the apparent shear stress on plane A-A is given by the following:

$$\tau = \mu du/dy - \rho u'v' = \tau_{lam} + \tau_{turb}$$

Note that ifthe flow is laminar. $u' = v' = 0$ so that $u'v' = 0$ and reduces to the customary random molecule-motion-induced laminar shear stress, $\tau_{lam} = \mu du/dy$. For turbulent flow it is found that the turbulent shear stress. $\tau_{turb} = \rho u'v'$, is positive. Hence the shear stress is greater in turbulent flow than in laminar flow. Note the units on τ_{turb}, are (density) (velocity) ^{2} =N/m2, as expected. Terms of the form $-\rho u'v'$ (or $-\rho v'w'$, etc.) are called Reynolds stresses in honor of Osborne Reynolds who first discussed them in 1895.

It is seen that the shear stress in turbulent flow is not merely proportional to the gradient of the time-averaged velocity, u(y). It also contains a contribution due to the random fluctuations of the x and y components of velocity. The density is involved because of the momentum transfer of the fluid within the random eddies. Although the relative magnitude aide of τ_{lam} compared to τ_{turb} is a complex function dependent on the specific flow involved, that the shear stress is proportional to the distance from the centerline ofthe pipe. In a very narrow region near the wall (the viscous sub layer), the laminar shear stress is dominant. Away from the wall in the outer layer, the turbulent portion of the shear stress is dominant. The transition between these two regions occurs in the overlap layer. Typically the value of τ_{turb} is 100 to 1000 times greater than τ_{lam} in the outer region, white the. Converse is true in the viscous sub layer. A correct modeling of turbulent flow is strongly dependent on an accurate knowledge of τ_{turb}. This, in tum requires an accurate know ledge of the fluctuations and U or pu' U .As yet it is not possible to solve the goveming equations for these details of the flow, although numerical techniques using the largest and fastest computers available have produced important information, about some of the characters of turbulence. Considerable effort has gone into the study of turbulence. Much remains to be leamed. Perhaps studies in the new areas of chaos and fractal geometry will provide the tools for a better understanding ofturbulence.

The viscous sub layer is usually a very thin layer adjacent to the wall. since the fluid motion within this thin layer is critical in terms tat the overall flow (the no-slip condition and the wall shear stress occur in this layer), it is not surprising to find that turbulent pipe flow properties can be quite dependent on the roughness of the pipe wall, unlike laminar pipe low which is independent of roughness. Small roughness elements can easily disturb this viscous sub layer, thereby affecting the entire flow. An altemate form for the shear stress for turbulent flow is given in terms of the eddy viscosity, η.

This extension of laminar flow terminology was introduced by J. Boussinesq, a French scientist, in 1877. A though the concept of an eddy viscosity is intriguing, in practice it is not an easy parameter to use, unlike the absolute viscosity , μ, which is a known value for agiven fluid, the eddy viscosity is a function of both the fluid and the flow conditions. That is, the eddy viscosity of water cannot be looked up in handbooks-its value changes from one turbulent flow condition to another and from one point in a turbulent flow to another.

The inability to accurately determine the Reynolds stress, pıru, is equivalent to not knowing the eddy viscosity. Several semi empirical theories have been proposed (Ref3) to determine approximate value of n. L. Prandlt (1875- 1953), a German physicist and aerodynamicist, proposed that the turbulent process could be viewed as the random transport of bundles of fluid particles over a certain distance, ℓ_m , the , mixing length. From a region of one velocity to another region ofa different velocity. By the use of some adhoc assumptions and physicalreasoning, it was concluded that the eddy viscosity was given by;

$$\eta = \rho \ell_m \cdot du/dy$$

Thus, the turbulent shear stress is

$$T_{turb} = \rho \ell_m^2 (du/dy)^2$$

The problem is thus shifted to that of (determining the mixing length, ℓ_m Further considerations indicate that ℓ_m is nota constant throughout the flow held. Near a solid surface the turbulence is dependent on the distance from the surface. Thus, additional assumptions are made regarding how the mixing length varies throughout the flow.

All-encompassing, useful model that can accurately predict the shear stress throughout a general incompressible, viscous turbulent flow. Without such information it is impossible to integrate the force balance equation to obtain the turbulent velocity profile and other useful information, as was done for laminar flow.

3.3.3 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 fromthe wall: the viscous sub layer very near the pipe wall, the overlap region, and the outer turbulent layer throughout the center portion of the flow. Within the viscous sub layer the viscous shear stress is dominant compared with the turbulent (or Reynolds) 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 sub layer the fluid viscosity is an important parameter; the density is unimportant. JTI.the outer layer the opposite is true. By a careful use of dimensional analysis arguments for the flow each layer and by matching of the results in the common overlap layer, it has been pôssibleto

obtain the following conclusions about the turbulent velocity profile in a smooth pipe.
In the viscous sub layer the velocity profile can be written in dimensionless from as;

$$u/u^* = yu^*/v$$

Where y = R - r is the distance measured from the Wall, is the time-average-d .x component of velocity, and u* is termed the friction velocity. Notethat u* is not all actual velocity of the fluid, it is newly a quantity that has dimensions ofvelocity.
Dimensional analysis arguments indicate that in the overlap region the velocity should vary as the logarithmic ofy, thus, the following expression has been proposed;

$$\frac{u}{u^*} = 2.5 \quad \ln\left(\frac{yu^*}{v}\right) + 5.0$$

Where the constants 2.5 and 5.0 have been determined experimentally. For regions not too close to the smooth wall, but not all the way out to the pipe center, equation above gives a reasonable correlation with the experimental <lata. Note that the horizontal scale is a logarithmic scale. This tends to exaggerate the sizeof.the viscous sub layer relative to the remainder ofthe flow shown. The turbulent profil es 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 Bemoulli equation and by assuming a fictitious uniform velocity profile. Since most flows are turbulent and turbulent flow tends to have nearly uniform -velocity p.r?ples, the usefulness of the Bemoulli equation and the uniform profile assumption is not unıexpectıeq.Qf course, many properties ofthe flow cannot be accounted for with out.includingyisc91.1sy:ff'eçt.

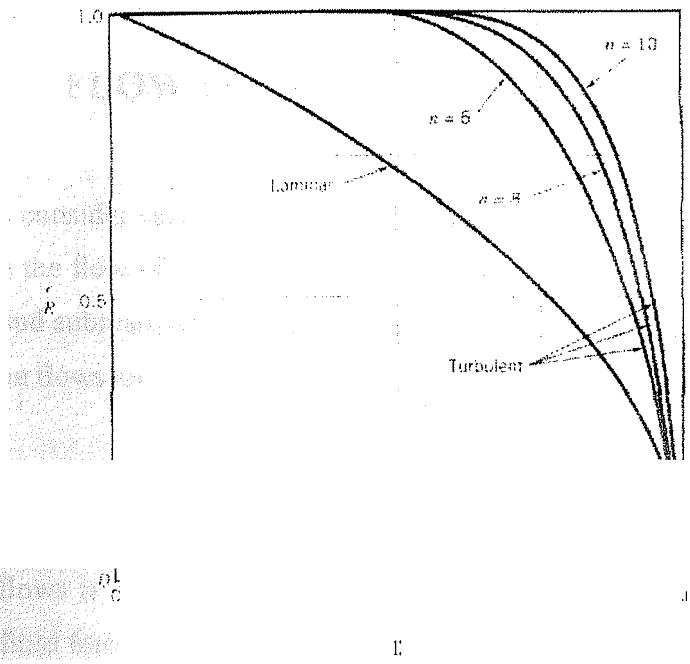


Figure 3.6 Typical lamina flow and turbulent flow velocity profiles

3.4 CONCLUSION

In this chapter we have discussed the very important topics that are related to the pipe flow. A:fter explaining certain keys difference between laminar and turbulent flow by reviewing Reynolds's classic experiment. We used for laminar flow the Newton viscosity law which is valid only for parallel flow. In more general flows, one must use a more general viscosity law for which the Newton viscosity law is a special case. We can prove rigorously the assumptionmade for parallel flow concerning pressure at a sectional pipe. Thus, for laminar pipe flow we were able to analytically formulate the velocity profile to be a paraboloidal surface of revolution and we were able to drive a head loss formula. Next we considered turbulent pipe flow. We explained how turbulence gives rise to a so-called apparent stress just as the transport of molecules gives rise a viscous stress. We pointed out that near a boundary the viscous stress dominate and further out from the boundary the apparent stress dominate with a region of overlap in between where both discus effects and turbulence effects significant

CHAPTERIV

FLOW OVER IMMERSED BODIES

In this chapter we consider various aspects of the flow over bodies that are immersed in a fluid. Examples include the flow of air around airplanes, automobiles, and falling snow flakes, Of the flow of water around submarines and fish. in these situations the object is cornpletely surrounded by the fluid and the flows are termed extemal flows.

Extemal flows involving air are often termed aerodynamics in response to the important extemal flows produced when an object such as an airplane flies through the atmosphere, Although this field of external flows is extremely important, there are many other examples that are of equal importance. The fluid force lift and drag on surface vehicles has become a very important topic. By correctly designing cars and trucks, it has become possible to greatly decrease the fuel consumption and improve the handling characteristics ofthe vehicle. Similar efforts have resulted in improved ships, whether they are surface vessels surrounded by two fluids, air and water Of submersible vessels, surrounded completely by water.

Other applications of external flows involve objects that are not completely surrounded by fluid, although they are placed in some external-type flow. For example, the pro per design ofa building must include consideration of the various wind effects involved.

As with othef areas of fluid mechanics, two approaches theoretical and experimental are used to obtain information on the fluid forces developed by extemal flows. Theoretical techniques can provide much ofthe needed information about such flows. However, because ofthe complexities of the goveming equations and the complexities of the geometry of the objects involved, the amount of information obtained from pufely theoretical methods is limited. With current and anticipated advancements in the a:fea of computational fluid mechanics, it is likely that computer prediction of forces and comp licated :flow pattems will become more readily availab le.

Much of the information about extern.a.Ffl.owsic6:rriesfrom experiments carried out, for the most part, on scale models of the actual objects. Such testing includes the of model airplanes, buildings, and even entire cities. In some instances model, is tested in wind tunnels. Better performance of cars, bikes, skiers, objects has resulted from testing in wind tunnels. The use of water tunnels and provides useful information about the flow around ships and other objects.

In this chapter we consider characteristics of external flow past a variety of objects. We investigate the qualitative aspects of such flows and leam how to determine the various forces on objects surrounded by a moving liquid.

4.1 GENERAL EXTERNAL FLOW CHARACTERISTICS

A body inımersedtin a 'moving fluid experience a resultant force due to the interaction betweeh the body and the fluid surrounding it. In some instances such as an airplane flying through still air the fluid far from the body is stationary and the body moves through the fluid with velocity U, In other instances the body is stationary and the fluid flows past the body with velocity U. In any case, we can fix the coordinate system in the body and treat the situation as fluid flowing stationary body with velocity U, the 'upstream velocity. For the purposes of this project, assume that the upstream velocity is constant in both time and location. That is, there constant velocity fluid flowing past the object. In actual situations this is often example, the wind blowing past a smokestack is nearly always turbulent and gusty ly not of uniform velocity from the top to the bottom ofthe stack. Usually the d non-uniformity are of nıinor importance.

Even with a flow, the flow in the vicinity of an object may he unsteady. Examples of this that is sometimes found in the flow past airfoils, the regular that sing in a wind, and the irregular turbulent fluctuations in the wake

The structure of an external flow and analyzed often depend on the nature of the body can be no truly two-dimensional bodies-nothing extends to are sufficiently long so that the end effects are negligibly small. Another classification of body shape can be made depending on whether the body is streamlined or blunt. The flow characteristics depend strongly on the amount of streamlining present. In general streamlined bodies (i.e.., airfoils. racing cars. ete.) have little effect on-the surrounding fluid, compared with the effect that blunt bodies (i.e., parachutes, buildingss-etcôthave on the fluid. Usually, but not always, it is easier to force a streamlined body thrôügh a fluid than it is to force a similar-sized blunt body at the same velocity. There are important exceptions to this basic rule.

4.1.1 LiFT ANDDRAG CONCEPTS

When any hotlyrtıô\Testhrough a fluid, an interaction between the body and the fluid occurs; this effect can be descı-ibedfoterms ofthe forces at the fluid-body interface. This can be described in terms of the stress.es.--wallshear stresses, ·rw, due to viscous effects and normal stresses due to the pressure, p, typical)sheafstress and pressure distributions are shown in figs below. Both shear stress and pressureva.ryin magnitude and direction along the surface.

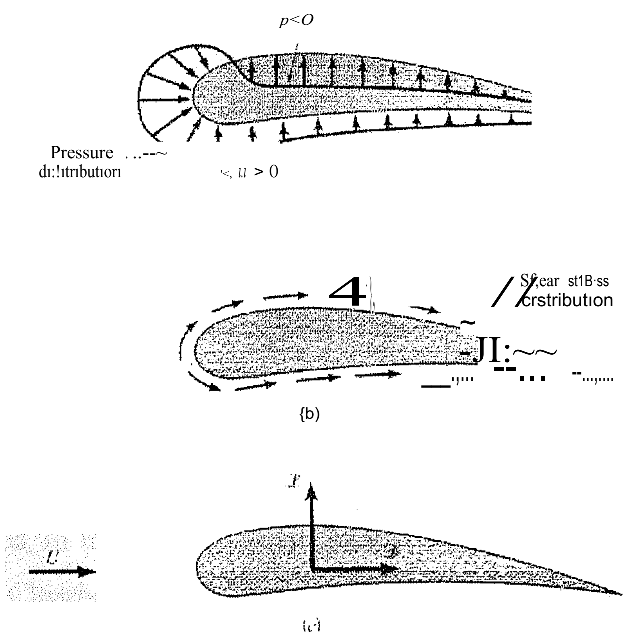


Figure 4.1 Forces from the surrounding fluid on a 2-dimensional object.

It is often useful to know the detailed distribution ofshear stress and pressure over the surface of the body, although such information is difficult to obtain. Many times, however, only the integrated of resultant effects of these distributionsrer» needed. The resultant force in the direction of the upstream velocity is termed th~ dta.g; p, and the resultant force normal to the upstream velocity is termed the lift, L, as is indicated in Fig. for some three-dimensional bodies there may also be aside force that is perpendiculaftotheplane containing D and L.

4.1.2 CHARACTERISTICS OF FLOW PAST AN OBJECT

Extemal flows past object encompass an extremely wide variety of fluid mechanisms phenomena. Clearly the character of the flow field is a function of the shape of the body. Flows past relatively simple geometric shapes are expected to have less complex flow fields than flows past a coriipleX: sha.pe süch as a.ii airplane Of a tree. However, even the simplest-shaped objects produce rather complex flows.

For a given-shaped object, the characteristics of tile flow depend very strongly on various parameters such as size, orientation, speed, and fluid properties. According to dimensional analysis afguriients, the chafa.ctef of the flow should depend on the various dimensionless parameters involved. For typical external flows the most important of these parameters are the Reynolds number, $Re = \rho Ul/\mu = Ul/v$, the Mach number, $Ma=U/c$. and for flows with a free surface, the Froude number, Fr.

For the pf~s~rit, we 6önsidef how the external flow and its associated lift and cfrag vary as a ... function of Reynolds number. Recall that the Reynolds number represents the ratio ofinertial effect s to viscous effects: In the absence of all viscous effects (μ =0). The R.eynôldsfiürnber is infinite. On.the other ha.rid,/iithe absence of all inertial effects (neğligiblelıass ör p=0). The Reynolds number is zero. Glea.tly,a.riyactualflow will haveaR.eyh.ôldsföimbe:rbetween (but not including) these two extremes, Theiia.ttı:reôftthefloWpa.stabôdydeperids strongly on whether Re>>l or Re<<l.

Most extemal flow's with which we are fariiiliafa.re)a.s.socia.tedwith moderately sized objects with a characteristic length on the order of 0.01 m < U< 10 m. In addition, typical upstream velocities are on the order of 0.01 m/s < U< 100 m/s and the fluids involved are typically water or air. The resulting Reynolds number range for such flows is approximately $10<Re<10^9$. As a rule of thumb, flows with Re>100 are dominated by inertial effects, whereas flows with Re<1 are dominated by viscous effects. Hence, most familiar external flows are dominated by inertia.

On the other hand, there are many external flows in which the Reynolds number is considerably less than 1, indicating in some sense that viscous forces are more important than inertial forces. The gradual settling of small particles of dirt in a lake or stream is governed by low Reynolds number flow principles because of the small diameter of the particles and their small settling speed. Similarly the Reynolds number for objects moving through large viscosity oils is small because μ is large. The general differences between small and large Reynolds number flow past streamlined and blunt objects can be illustrated by considering flows past two objects-one a flat plate parallel to the upstream velocity and the other a circular cylinder.

One of the great advancements in fluid mechanics occurred in 1904 as a result of the insight of Ludwig Prandlt (1875-1953), a German physicist and aerodynamicist. He conceived of the idea of the boundary layer-a thin region on the surface of a body in which viscous effects are important and the outside of which the fluid behaves essentially as if it were inviscid. Clearly the actual fluid viscosity is the same throughout; only the relative importance of the viscous effects due to the velocity gradients is different within or outside of the boundary layer. By using such a hypothesis it is possible to simplify the analysis of large Reynolds number flows, thereby allowing solution to external flow problems that are otherwise unsolved.

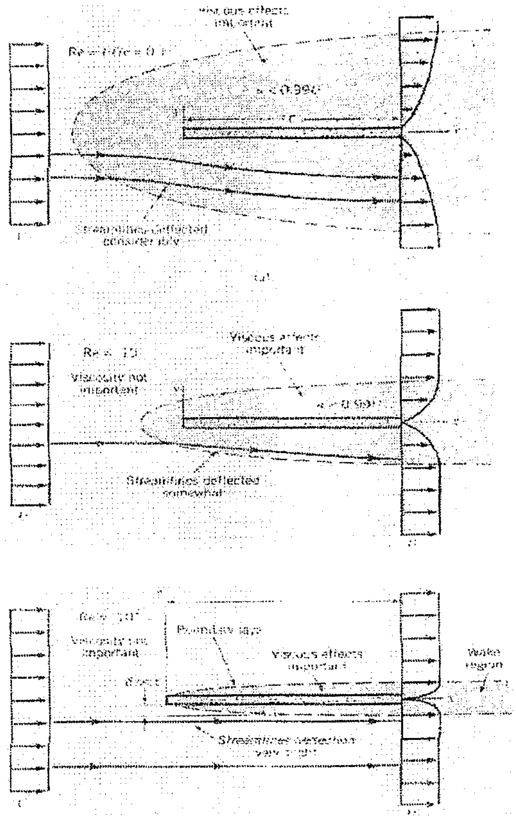


Figure 4.2 Chatactefőfthe\steady, viscous flow pasta flat plate parallel to the upstream.

As with the flow past the flat pla.te descriöed abôve, the flow past a blunt object (suchasUa. circular cylinder) also varies with Reynolds number. In general, the larger the Reynolds IIII mber, the smaller the region ofthe flow field in which viscôtiSe:ffects are important. For object s that are not sufficiently streamlined, however, an additiona] ctιifacteristic ofthe flöw is 8Bserved. This is termed flow separation and is illustrated in Fig. below.

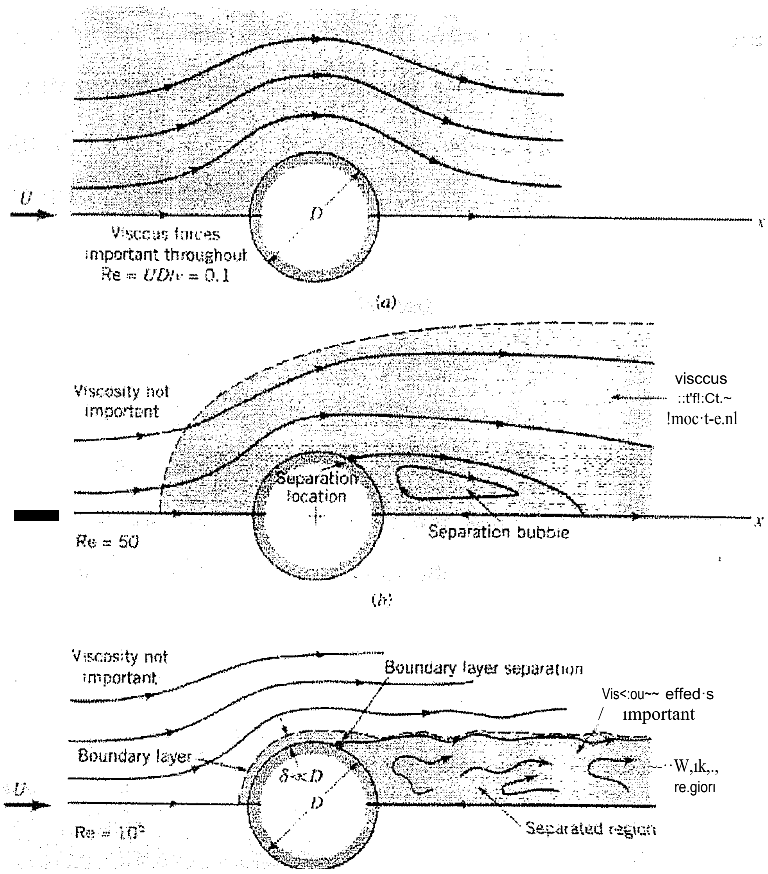


Figure 4.3 character of steady, viscous flow past a circular cvlinder

Low Reynolds number flow where Re = *UDi* v < 1 pasta cireular cylinder is characterizedby the fact that the presence of the cylinder and the accompanying viscous effects are felt throughout a relatively large portion ofthe flow field. For Re= UD/v = 0.1, the viscous effects are important several diameters in any direction from the cylinder. A somewhat surprising characteristic of this flow is that the streaınlines are essentially symmetric about the center of the cylinder-the streamline pattem is the saıneitıfront ofthe cylinderas it is behind the cylinder.

As the Reynolds number is increa.sed,iheregion ahead of the cylihdefirtwhich viscous effects are important becomes smaller, with the visöös region exteridirigonly a. short distance ahead of the cylinder. The viscous effects are cortvicted d<n..vnstream and the flow loses its symmetry. Another characteristic of extemal flows becöırıesiınpöıtant-----the flow separates from the body at

the separation location. With the increase in l}eynolds number, the fluid inertia becomes more important and at some Jocation on the body, denoted the separation location, the fluid's inertia is such that it carı.rı.ôt follow the curved patlı a.rourı.d 'to the rear of the body. The .result is a separation bubble behind the cylinder illwhichsbriieiof the fluid is actually flowing upstream, against the direction of the upstream flow.

At still larger Reynolds numbers, the area affecfoôby the viscoüs forces is forced farther downstream until it involves only a thin (ö < D)bburı.daıy laye'f()rı. the frônt portion of the cylinder and an irregular, unsteady (perhaps turbulerı.t)wake feğibrı. thafexterı.d fardowıistream of the cylinder. The fluid in the region outside of the boundary la.yer arid wa.ke region flows as if it were in-viscid. Of course the fluid viscosity is the same thrôughôufthe entire flow field. Whether viscous effects are impottartt or not deperids ôrı. which •·teğiôrı ôftne' flôw<fieföWe considered. The velocity gradients within the boundary layer and wa.ke regions a.reifuuchla.rget than those in the remainder of the flow field. Since the shear stress is the product of the fluid viscosity and the velocity gradient, it follows that viscous effects are confined to the boundary layer and wake tegiôrı.s.

The characteristics for flow past a flat plate and a cylinder are typical of flows past streamlined and blunt bodies, respectively. The nature of the flow depends strongly on the Reynolds number. Most familiar flows are similar to the large Reynolds number flows, rather than the low Reynolds number situations.

4.2 BOUNDARY LA.YER CHARACTERISTICS

As was discussed in the previous section, it is often possible to treat flow p~şi an object as a combination of viscous flow in the boundary layer and in-viscid flow elsewhere.]30 undary layers is described as a very thin Iayer of fluid adjacent to a surface, in which viscosity is important, while outside this layer the fluid can be considered as frictionless or ideal. The bounda ry layer may be entirely laminar or it may be primarily turbulent with a viscous sub-layer. The thfokness δ of the boundary layer is usually defined as the distance from the boundary to the poinfwh ere velocity is 99% of the undisturbed velocity. This thick:rı.ess increases with the distance fronfthe leading edge ofa surface.

There is an important differenbe between flow around' immersed bodies and pipe flow. In pipe flow the bounder layers from the opposite walls of the pipe merged together after a certain distance and the flow becomes all boundary layers, while with immersed bodies, the bounder layers may reach a thickness of several inches, still small compared with the dimensions of the ideal fluid outside the boundary layers.

If the Rey11ôlds riumberis larğe eıiôugh;viscous effects are important only in the "'~···~"·~· regions near the object al1d i11the wake regiôrı behind the öbject. The boundary layer is neeaen flow fields to allow for the no-slip bou11dafycônditionthaf requires the fluid to cling to id surface that it flows past. Outside of the bottnda.ry la.yer the velocity gradients normal tô the flow are relatively small, and the fluid acts as if it were .in-viscid, even though the viscosity is not zero. A necessary condition'for this structure ofthe flow isthatthe Reynolds numbefoeila rge.

4.2.1 BOUNDARY LAYER STRUCTURE AND THICKNE SS ON A FLATPLATE

There can be a wide variety in the size ofa boundary layer and the structure of the flow within it. Part of this variation is due to the shape of the object on which the boundary layer forms. In this section we consider the simplest situation, one in which the boundary layer is formed on an infinitely long flat plate along which flows a viscous, incompressi ble fluid as is shown in fig. 9.7. Ifthe surface were curved, the boundary layer structure wouldbe more complex.

If the Reynolds number is sufficiently large, only the fluid in a relatively thinl)ô\.trı.dary layer on the plate will feef.fhe effect of the plate. That is, except in the region nextföfüıe/p'late the flow velocity will be> essentia.lly V=Ui, the upstream velocity. I or the infinitel-y!lông flat plate extendinğfrôm x::±:ötôx= oo, it is not obvious how to define the Reynolds number'lf ecause there is no chara.ctefisticlenğth.The plate has no thickness and is not of finite length.

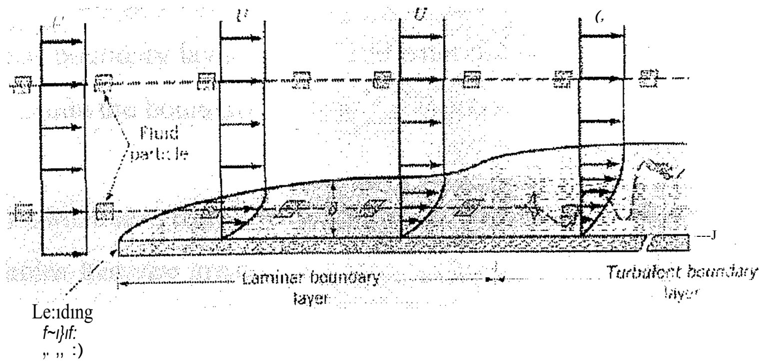


Figure 4.4 Distortion ofa fliıid partide as it flows within the boundary layer.

Fora finite lengthpla.te, it is clearthat the plate length l, can be used as the characteristic length. For anınfi11ıteİylö11.g plate We \ise X, the coordinate distance along the plate from the leading edge, as the chara.ctenS1:iclength :ıındtiefinethe Reynôlds number as Re; = Ux/v. Thus,i:föi!'a.rıy fluid or upstream velocity the ReYnôldStiurrıber will be sufficiently large for boundary laYer type flow if the plate is long enough. Physically, this means that the flow situations could he thought of as occurring on the same plate, but should be viewed by looking at longer p§rj: ions of the plate. Ifthe plate is sufficiently long, the Reyrıolds number Re=Ul/v i:S sufficiently large so that the flow takes on its boundary layer character except very near the Ieadiiig~d ge.

The details of the flow field near the leading edge are lost to our eyes because we are standing so far from the plate that we can not make out these details. On this scale the plate has negligible effect on the fluid a.head of the plate. The presence ﾠ plate is felt only in the relatively thin boundary layer and wake regions. ﾠ :d, PrandIt in 1904 was the first to hypothesize such a concept. It ﾠ major turning points in fluid mechanics analysis.

A better appreciation of the structure of the boundary layer flow can he obtained by cortsidering what happens to a fluid partide that flows into the boundary layer. A small rectangular'partide retains its original shape as it flows in the uniform flow outside of t he boundary layer. ünce it enters the boundary layer, the partide begins to distort because of the velocity gradient within the boundary layer-the top of the particle has a larger speed than its bottom. The fluid particles do not rotate as they flow along outside the boundary layer, but they begin to rotate once they pass through the fictitious boundary layer surface and enter the world ofviscous flow. The flow is said to be irrotational outside the boundary layer and rotational within the boundary layer.

At some distance downstream from the leading edge, the boundary layer flow becomes turbulent and the fluid particles become greatly distorted because of the random, irregular nature of the turbulence. One of the distinguishing features of turbulent flow is the occurrence of irregular mixing fluid parcels that range in size from the smallest fluid particles up to those comparable in size with the object of interest. For laminar flow, mixing occurs only on the molecular scale. This molecular scale is orders of magnitude smaller in size than typical size scales for turbulent flow mixing. The trartsitionifrom laminar to turbulent flow occurs at a critical value of the Reynolds number Re On the order of $2 * 10^5$ to $3 * 10^6$, depending on the roughness of the surface and the amount of turbulence in the upstream flow.

The purpose of the boundary layer on the plate is to allow the fluid to change its velocity from the upstrea.m.\valueof U to zero on the plate. Thus, V= 0 at y = 0 and V:::: Ui-a.ty=ô, with the velocity profile U = u(x,y) bridging the boundary layer thickness. In actua.lify (both mathemaficallya.ndphysically), there is no sharp edge to the boundary layer. Tha.fis, *u* - U as we get fartheffrôrri the plate; it is not precisely u = U at y = ö. We define the boundary layer thickness, δ, as that distaiice frôrii the plate at which the flüid' veföcify is within some arbitrary value of the upstream velôcify. typica.lly, as indicated in Fiğ. ·4.s,

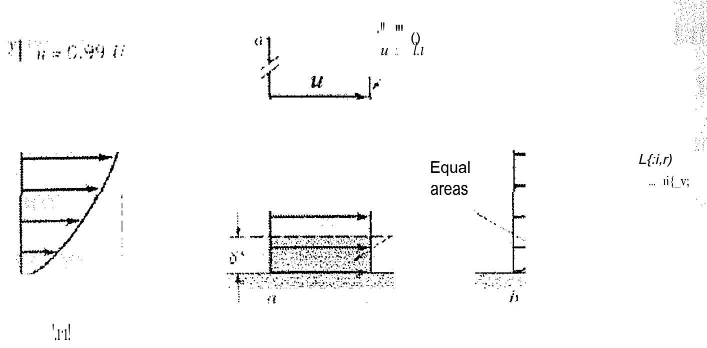


FIG4.5. Boundary layer thickness

$$\delta = y \text{ where } u = 0.99U$$

To remove this' arbitra.ri.ness(i.e... what is so special about 99%; why not 98 %?), the following definitions are inttoduced Shown in Fig. 9.8b, are two velocity profiles for flow past a flat plate-one if there were no viscosity (a uniform profile) and the other if there is viscosity a.n.d zero slip at the wall (the boundary layer profile). Because of the velocity deficit, U - u, within the boundary layer, the flow rate across section b-b is less than that across section a-a. Howevet; if we displace the pla.te at section a-a by an operate amount δ^*, the boundary layer displacemen.t thickness, the ±i&W ra1:e1&t6~s ~ach section will be identical this true if;

$$\delta^* = \int_0^{\infty} (1-u/U)dy.$$

The displacement thickness represents the amount that the thickness of the body must be increased so that the fi.ctitious uniform in-viscid flow has the same mass flow .ratēproperties as the actual viscous flow. It represents the outward displacement of the streamlines caused by the viscous effects on the plate. This idea allows us simulate the presence that the boundary layer as on the flow outside of the boundary layer by adding the displacement thickn.eSSto the actual wall and treating- the flow over the thickened body as an in-viscid flow, .An.other boundary layer thickness definition, the boundary layer momentum thickness, θ, .i§ ôftefr;ı.iȩd when determining the drag on an object. Again because of the velocity defi.cit, IJ..uf!itzy the boundary layer, the momentum flux across section b-b in Fig. 4.5 is less than that acröSs section a-a. This deficit in momentum flux forthe actual boundary layer flow is given-by;

$$\int \rho u(U - u)\, dA = \rho b \int u(U - u)dy$$

Which by defin ition is the momentum flux inala yer of uniform speed U artdtlii ckness θ. All three boundary layerthickness definitions, o, o* and 8, are of use in boundary>layer analyses. The boundary layer concept is based on the fact that the boundary layer is thirt.For the flat plate flow this-means-tharetany location x along theplate, o<<x. Similarly, o* <<x arıd8-<i-<i x. Again, this is 'tnıe iLwe do not get too close to the leading edge of the plate (i.e., not closer than Rex=Ux/v= 1000 or so). The structure and properties of the boundary layer flow depend on whether the flow is laminar or turbulent.

4.2.2 MOMENTUM ..JNTEGRAL.BOUNDARY LAYER EQUATION FOlt AFLATPLATE

üne of the inipottanf aspects of boundary layer theory is the determination of the drag caused by shear forces on a body. As was discussed in the previous section, such results can be obta.irıed from the goveming differential equations for laminar boundary layer flow. Since these solutiôrıs are extremely difficult to obtain; itis of interest to have an altemative approximate methôd.>'fhe momentum integral niethod desCtibed in this section provides such an altemative. We consider the uniform flow past a flat plate and the :fixed control volume as shown in Figure 4.6--)Irı agreement with advanced theofy> and' experiment; we assume that the pressure iS<cônS tant throughout the flow field. The floWerıteringtheCdntrol volume at the leading edgeôftlı e plate [section (1)] is uniform, while the velocity ofthe flôw exiting the control volurn.e[Section (2)] varies from the upstream velocity at the edge of the boundary layer to zero velocity'§n_ the plate.

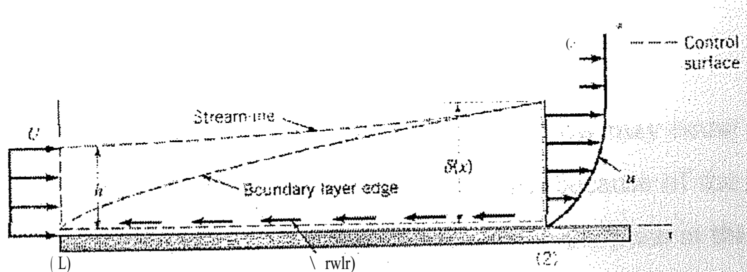


Figure 4.6. Control volume used in the derivation ofthefr1011momentum integral equation for boundary layer flow.

The increase in drag perJength of the plate di /dx, occurs at the expense of~fli ncrease of the momentum boundaıyfayer thickness which represents a decrease in the momentu.fu of the fluid. The usefulness ôfJhisrelationship lies in the ability to obtain approximate boundaryla: yer results easily by usiıngra,the(cru.de assumptions. For example, ifwe knew the detailed velocitypf ·ofile in the boundary layer.

4.2.3 TRANSI'fl()N\FROM LAMINAR TO.TURBULENT FLOW

Some analyticafresuffsa.refesfricted to laminar boundary Iayer flows along a flat plate with zerö pressure gradients. They agree quite well with experimental results up to the point where the boundary layer flow becornes turbulent, which will occur for any free stream velocity and any fluid provided the plate is long enough. This is true because the param eter that govems the transition.to ~rb~l~ıfi~o'1'iisith!0~r~o.lds number- in this case the Reynolds number basedon the distance fromtheleading edge ofthe plate, Re- = Ux / v.

The value of the Reyrıolds rıuriıbet a.tthe transition location is a rather complex functiô n of various parameters involved, includingthe roughness of the surface, the Curvature ofthesu rface, and some measure of the disturbances in the flow outside the boundary layer. On a flat plate with a sharp leading edge in a typical air stream, the transition takes place at a distance x from the leading edge given by $Re_{xcr} = 2*10^5$ to $3*10^6$. Unless otherwise stated, we will US~ $Re_{xcr} = 5*10^5$ in our calculations.

The actual transition from laminar to turbulent boundary layer flow may\ğ ccur over a region of the plate, not at a specific single location. This occurs, in part, becaµs e of the spottiness of the transition. Typically, the transition begins at random locations on thepJ ate in the vicinity of Rex= Re-«. These spots grow rapidly as they are convicted downstre am until the entire width of the plate is covered with turbulent flow. The complex process§fötr: ansition from laminar to turbulent flow involves the instability of the flow field. Small disturô ances imposed on the boundary layer flow will either grow or decay , depending on where theidi sturbance is introduced into the flow.

If these disturbances occur at a location with Rex< Rexcr they will die out and the boundary layer will retum to lamirıar flow at that location. Disturbances imposed at a location-with Rex> Rexcr will grow and transform the boundary layer from downstream ofthis location into turbulerıce. Transition from laminar to turbulent flow al.so involves a noticeable change in the share~f+the boundary layer velocity profile. Typical profiles obtained in the neighborhood of the transition location are indicated in the figure below. The turbulent profiles are flatter, have a larger velôcify; the complex process of transition from laminar to turbulent flow involves the instability of the flow field. Small disturbances imposed on the boundary layer flow will either grow or decay, depending on where the disturbance is introduced into the flow. If these disturbances occur at a location with Rex<Rexcr they will die out and the boundary layer will return to laminar flow at that location. Disturbances imposed at a location with Rex> Rese- will grow and transform the boundary Iayer from .downstream of this location into turbulence. Transition from laminar to turbulent flow also involves a noticeable change in the shape of the boundary layer velocity profile. Typical profiles obtained in the neighborhood of the transition location are indicated in the figure below. The turbulent profiles .are flatter, have a larger velocity gradient at the wall, and produce a large boundary layer thickness than do the laminar profiles.

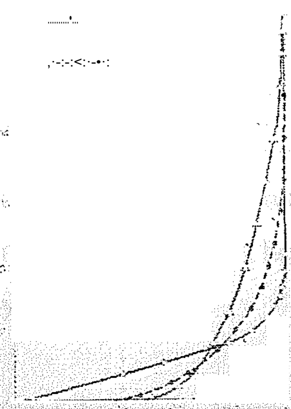


Figure 4.7 Typical boundary layer profiles on a flat plat for laminar, transitional, and turbulent flow

4.2.4 TURBULENT BOUNDARYLAYER FLOW

The structure of turbulent boundary layer how is very cornplex, randorn, and irregular. It shares many of the characteristics described for turbulent pipe flow. In particular, the veiocity at any given location *in* the tlow is unsteady in a random fashion. The flow can be thought of as a jumbled mix of intertwined eddies of different sizes. The various fluid quantities involved like mass, momentum, energy are confected downstream in the free-stream direction as in a laminar boundary layer. For turbulent flow they are also confected across the boundary layer in the direction perpendicular to the plate by the random transport of finite-sized fluid particles associated with the turbulent eddies. There is considerable mixing involved with these finite-sized eddies considerably more than is associated with the mixing found in laminar flow where it is confined to the molecular scale. Although there is considerable random motion of fluid particles perpendicular to the plate, there is very little net transfer of mass across the boundary layer, the largest flow-rate by far is parallel to the plate.

There is, however, a considerable net transfer of x component of momentum perpendicular I to the plate because of the random motion of the particles. Fluid particles moving toward the plate in the negative y direction have some of their excess momentum because they come from areas of higher velocity removed by the plate. Conversely, particles moving away from the plate in the positive y direction gain momentum from: the fh:ı.id beca.use thef/cônıe :fforn areas öf.fowef velocity. The net result is that the plate acts as a mometıtum sink, continually extracting momentum from the fluid. For laminar flows, such cross-stream transfer of these properties takes place solely on the nıolecular scale. For turbuletıt flow the randomness is associated with fluid particle mixing. Consequently, the shear force for turbulent boundary layer flow is considerably greater than it is for laminar boundary layer flow.

There are no exact solutions or turbulent boundary layer flow. Since there ıs no precise expression for the shear stress in turbulent flow, solutions are not available for turbulent flow. However, considerable headway has beenmade in obtaining numerical computer) solutions for turbulent flow by using approximate shear stress relationships. Also, progress is being made in the area of direct, full numerical integration of the basic goveming equations; the Navier-Stokes equations. Approximate turbulent boundary layer results can also be obtairrecirıby use of the momentum integral equation, which is valid for either laminar or turbulentflô.w.CXM hat is needed or the use of this eqııation are reasonable approximations to the velocity profile u#<l?J' g(Y), where Y = y/ ^{8} and u is the time-averaged velocity (the over bar notation, u, has been dfôpped for convenience) anda functional relationship describing the wall shear stress. For lamiııaı+.fl ow the wall shear stress was used as -rw=μ (du/dy)y. Intheory, such a technique should workforhfrb ulent boundary layers also. However, the details of-the velocity gradient at the wall are nôt:w-ell understood for turbulent flow. Thus, it is necessary. to use some empirical relationship föf.the wall shear stress.

4.2.5 EFFECTS OF PRESSURE GRADIENT

The boundary layer discussed in previous sections has dealt with flow along a flat plate in which the pressure is constant throughout the fluid. In general, when a fluid flows pastan object other than a flat plate, the pressure field is not uniform, if the Reynolds number is large, relatively thin boundary layers will develop along the surfaces. Within these layers the component of the pressure gradient in the streamwise direction is not zero, although the pressure gradient normal to the surface is negligibly small. Thatis, if we were to measure the pressure while moving across the boundary layer from the body to the boundary Iayer edge, we would find that the pressur~is essentially constant. However, the pressure does vary in the direction along the body surfa.ce if the body is curved. The variation in the free stream velocity, Us, the fluid velocity at theiedge of the boundary layer, is the cause ofthe pressure gradient in the boundary layer. The chara.cteristics of the entire flow both within andoutside. Öf the boundarylayer are.often highly dep~rtd~nt on the pressure gradient effects on the fluid within the boundary layer.

Fora flat plate parallel to the upstream flow, the upstream velocity and thefree""stream velocity are equal U=Urs. This is a consequence of the negligible thickness of thefp late. For bodies of nonzero thickness, these two velocities are different. This can be ·Seeniri the flow past a circular cylinder of diameter D. The upstream velocity and pressure are Ua.ncJnpo, respectively. If the fluid were completely inviscid (μ = 0), the Reynolds number: wc:ıufötb e infinite (Re=∞) and the streamlines would be symmetrical.. The fluid velocity alöriğthesu rface would vary from Ufs= 0 at the very front and rear of the cylinder to a maximumofUi~Z.: U at the top and bottom of the cylinder (point. C'). The pressure on the surface of the cylinder cal about the vertical mid-pları.eöfthecylinder, reaching a maximum value po+pU2/2 the n pressure at both the front and back ofthe cylinder, anda minimum of po- 3pU2/2 at the top ıttom of the cylinder.

Due -to the abserı.ce of viscosity and the symmetry of the pressure distribution for invisci d flow pasta circular cylinder, it is clear that the drag onthe cylinder is zero. Although it is not obv ious, it can be shown that the drag is zero for any object thatdoes not produce a lift in an inviscid.-fl:ı.ıi d. Based on experimental evidence, however, we knowthatthere must be a net drag. Clearly,.isirice there is no purely .inviscid fluid, the reason for the observed drag must lie on the shoulders ofthe viscous effects.

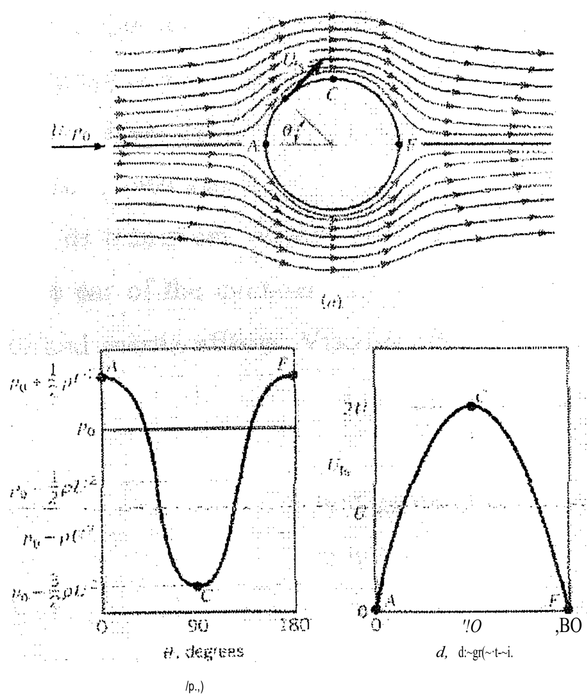


Figure 4.8. Inviscid flow pasta circular cylirider.

To test this hypothesis, we could conduct an experiment by 111.easuririg the drag on an object such as a circular cylinder in a series of fluids with decreasing valües ôf viscosity. To our initial surprise we would hind that no matter how small we make the -vıscosity we would measure a finite drag, essentially independent of the value of μ. th.is leads to what has been termed

D'Alembert paradox, the dragon an object in an inviscid fluid is zero, but the drag.on an.objectin a fluid with vanishing .small but nonzero, viscosity is not zero.

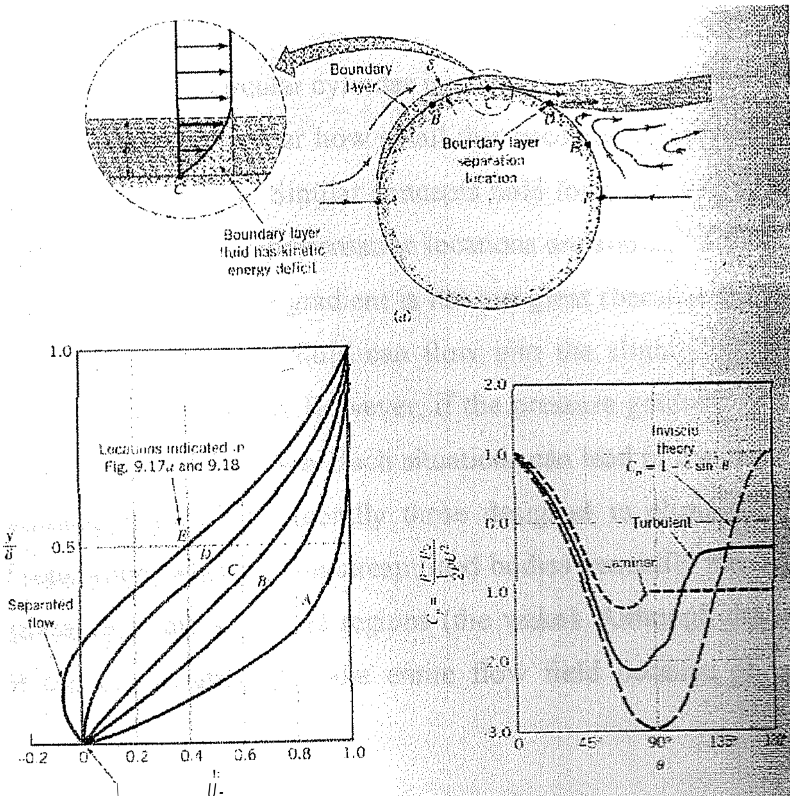
The reason for.rheabove paradox can be desetibedin-terms ofthe effect ofthe pressure gradient on boundary .layer flow. Consider large Reyrtolds number flow of a real viscous fluid past a circular cylinder. e expect the viscous effectstoibe confined to thin boundary layers near the surface. This allows the fluid to stick (V=O) .to the sUrface-a necessary condition for any fluid, provided μ;t: 0. The basic idea of boundary layer theory is that the boundary layer is thin enough so that it does not greatly disturb the flow outside .the bôunda.rylayer. Based on this reasoning, for large Reynolds numbers the flow throughout mostoftheiflowfieldwould be expected to be the inviscid.flowıfield as is indicated in figure 4.8a.

The pressure distribution is imposed on the boundary layer flow along. the surface Of the cylinder. In fact, there is negligible pressure variation across the thin boundary layer so tha.tthe pressure within the boundary layer is that given by the inviscid flow field. This pressure distribution along\Jhe cylinderis suchthat the stationary fluid at the nose of the cylinder (Ufs = 0 at 8 ==.O()}is accelera.ted.to itsimaxitnum velocity (Ue =2Uat 8- 90°) and then is decelerated back to zero velocityattheieatbfthe cylinder (Ue=O at 8=180°). This is accomplished by a balance between pressure andirıertia effects; Viscous effects are absent for the inviscid flow outside the boundary layer.

Physically, in the absence of viscous effects, a fluid partide traveling from the front.to the back of the cylinder coasts down the 'pressure hill" from 8 = 0° to 8 = 90° (from point A to Cin Fig. 4.8b) and then back up the hill 8 = 180° (from point C to F) without any loss of energy. There is an exchange between kinetic and pressure energy, but there are no energy losses. The same pressure distribution is imposed on the viscous fluid within the boundary layer. The decrease in pressure in the direction of flow along the front half of the cylinder is termed a favorable pressure gradient. The increase in pressure in the direction of flow along the rear half of the cylinder is termed an adverse pressure gradient.

Consider a fluid partide within the boundary layer, in its attempt to flow from A to F it experiences the same pressure distribution as the particles in the free stream ınını.~q.ia.tely eutside the boundary layer-the in-viscid flow field pressure. However, because of th~i~iscôuse.rfects involved, the particle in the boundary layer experiences a loss of energy as it flows along,'I'his loss means that the parti ele does not have enoı.ıgh 'energy to coast all of the way Up the pressure hill (from C to F) and to reach point F at the rear of the cylinder. This kinetic energy deficitis seen in the velocity profile detail at point C shown in Fig. 4. 9a. Because of friction, the boundarş' layer fluid cannot travel from the front to the rea:r of the cylinder.

The situation is similar to .a bicyclist coastirıg'down a hill and up the other side of the valley. If there were no friction the rider starting with zero speed could reach the same height from which he or she started. Clearly frictien .(rolling resistance, a.erodynamic drag. ete.) causes a loss of energy (and mômerttunı),nıakirıgifjmpossible fortheTider to reach the height from which he or she started without supp}yingadditional energy (i.e., peddling). The fluid within the boundary layer does not have such an energy .supply. Thus, the fluid flows against the increasing pressure as far as it can, at which point the .boundary layer separates from (lifts off) the surface. This boundary layer separatiortis/indicatedin Fig. 4.9a. Typical velocity' profiles at representative locations alone the sutface are showrı in Fig. 4.9). At the separation location (profile D), the velocity gradientarthe wa.lkarıdthe\Vall shear stress are zero. Beyond that location (fr()m,l)to:E) there is reverse flow in the boundaryJayer.



Fiğure.4.9. Boundary layer characteristics on a circular cylinder

As is indicated in Fig. 4.9 because of the boundary layer separation, the average pressure on the rear half of the cylinder is considerably less than in that on the front half. Thus, a large pressure drag is developed, even though (because of small viscosity) the viscous shear drag may be quite small. D'Alembert paradox is explained. No matter how small the viscosity, provided it is not zero, therewil] be a boundary layer that separates from the surface, giving a drag that is, for the most.part, independent of the value of μ. The location of separation, the width of the wake region behind the object, and the pressure distribution on the surface depend on the nature of the boundary layer flow. Compared with a laminar boundary layer, a turbulent boundary layer flow has more kinetic energy and momentum associated with it because (1) the velocity profile is fuller, more nearly like the ideal uniform profile, and (2) there can be considerable energy associated with tile swirling, random components of the velocity that do not appear in the time averaged x component of velocity. Thus, as is indicated in Fig. 9.17c, the turbulent boundary layer can flow farther around the cylinder (farther tip the pressure hill) before it separates than can the laminar boundary layer.

The structure of the flow field past a circular cylinder is completely different for a zero viscosity fluid than it is fora viscous fluid; no matter how srnaffthe viscosity is, provided it is not zero. This is due to boundary layer separation. Similar concepts(p.'.oldfor other shaped bodies as well. The boundary layer velocity profiles at representative locationsare similar to those for flow past a circular cylinder, If the adverse pressure gradient is not too great (because the body is not too thick .in some sense), the boundary layer fluid can flow into the slightly increasing pressure region without separating from the surface. However, if the pressure gradient is too adverse the boundary layer will separate from the surface. Such situations can lead to the catastrophic loss of lift called staU. Streamlined bodies are generally those designed to eliminate (or at least to reduce) the effects of separation, whereas non-streamlined bodies generally have relatively large drag due to the low pressure in the separated regions (the wake). Although the boundary layer may be quite thin, it can appreciably alter the entire flow field because of boundary layer separation.

4.3 CLOSURE

In this chapter we Cônsföer variôtis a.specfs bfthe flôw ÔVer bodies that are immersed in a fluid. Then we analyzed the externalflöw chata.cteristics/The stftıcture of an extemal flow and the ease with which the flow can be described arıda.:rialyiedôftendeperid on the nature of the body in the flow. We Côil.sidered the interaction between the bôdf and the fluid which we described .its effects in ternis ôftheförces at the fluid-body intefface. Alsa how viscous effects ate irnpôrta.fü only in the boundary layerregions near the object and in the wake region beh.ind the ôojecf The Navier-Stokes equations was sirnplified for boundary layer flow analysis, a:ridhôwthe bôuiidafy layer equations can be wtitten in tetrtıs of similarity variables. As the n:ıôn:ı.eı:ittin:ı.i:riteğı-al method provides an approximate technique to analyze boundary •layef flow; FwJiere·We USe the approximate velocity profil es in it so we can obtain the approxirna.te Bôundary layer results.

We discussed about the boundary layer on a flat plate which becôn:ı.e ttirbulerıt if the plate is long enough. Alsa random transport of finite sized fluid particles ôccurs withitı turbulent boundary layers. and from the study we found out that there ate rıô e*actSôlutions available for turbulent boundary layer flows.

CONCLUSION

Our aim of this research was to discuss the lamtiı.affüfl:füleiitflowas a viscous pipe flow and as an external flow.

We began with the basic fundamentals of>fltiids mech.afücs by defining the fluid, its characteristics same as for the flow. With a brief on the factors affecting the flow; as we saw in chapter one where we explained the major factors'Uicı.tiXciifö, continuum, density, specifc volume and pressure, ete.

As for the second chapter we found out that the dimensions of mechanics are, force, length and time. As it proceed in Newton's second law of motion. With a discussion of dimensionless parameters (Reynolds number, Froude number, Weber number and the Mach number) which affect the flow.

In the next chapter we explained main characteristics of the pipe flow, when it is laminar and when it is turbulent. As we found out there are numerous ways to drive important pertaining to fully developed laminar pipe flow. Three altematives were discussed: 1. the F=ma, 2. the Navier-Stokes equations of motion, and 3. dimensional analysis methods. Also the transition from laminar to turbulent flow, then a brief on the turbulent flow and its shear stress where the fundamental differences between laminar and turbulent flow lies in the chaotic, rnnuvm behavior of the various fluid parameters. Where the turbulent parameters can be described in terms of mean and fluctuating portions. The relationship between fluid motion and shear stress is very complex for turbulent flow where this flow involves the random motions of finite sized fluid particles. From this we find out that the shear stress is the sum of a laminar portion and a turbulent portion where various ad hoc assumptions have been used to approximate turbulent shear stresses. Also a power law velocity profile approximates the actual velocity profile.

in the fourth chapter the subject was flow over immersed bodies (external flow). A body immersed in a moving fluid experience a resultant force due to the'ırıferaction between the body and the fluid surrounding it, where the shape of the body affects the flow characteristics. For extemal flows it is usually easiest to use a coordinate. Also the body interacts with the surrounding fluid through pressure and shear stresses. Next we explained how the character of flow past an object is dependent on the value of Reynolds number, where thin boundary layers may develop in large Reynolds number flows. Large Reynolds number flow fields may be divided into viscous and inviscid regions, i':flıe fluid particles within the boundary layer experience viscous effects where we defined the'böundary layer displacement thickness in terms ofvolumetric flowrate and the boundary layettrıô:rnenru.mthickness in terms ofmomentum flux. We simplified the Navier-Stokes equations for bourıdary layer flow analysis.

Also we discussed the transiti on offlow from·lamiriariôtutbulent where the boundary layer ona flat plate will become turbulent if the plate islôn.g'enôi.igh:As we explained in chapter three that there are no exact solutions available for turbulerit>bôi.indaıy Iayer flows, the same situation in extemal flows.

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