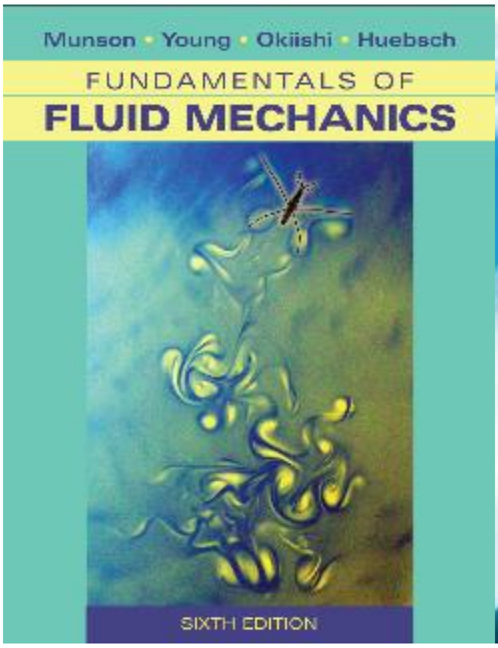
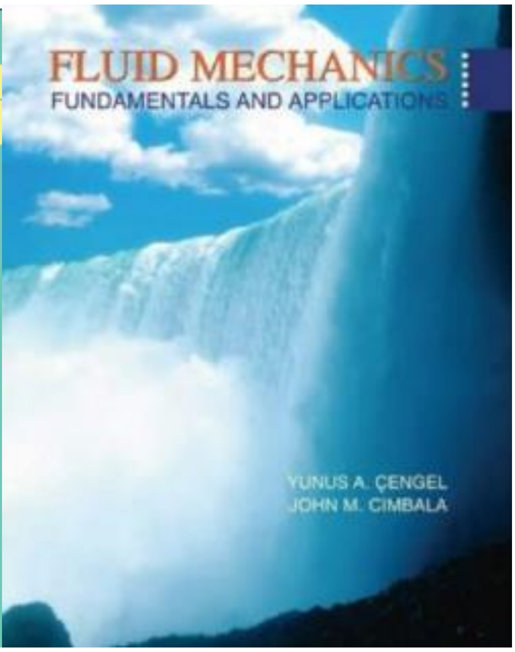
FLUID MECHANICS





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5. FLOW IN PIPES

Liquid or gas flow through *pipes* or *ducts* is commonly used in heating and cooling applications and fluid distribution networks. The fluid in such applications is usually forced to flow by a fan or pump through a flow section. We pay particular attention to *friction,* which is directly related to the *pressure drop* and *head loss* during flow through pipes and ducts. The pressure drop is then used to determine the pumping power requirement. A typical piping system involves pipes of different diameters connected to each other by various fittings or elbows to route the fluid, valves to control the flow rate, and pumps to pressurize the fluid.

The terms *pipe, duct,* and *conduit* are usually used interchangeably for flow sections. In general, flow sections of circular cross section are referred to as *pipes* (especially when the fluid is a liquid), and flow sections of noncircular cross section as *ducts* (especially when the fluid is a gas). Smalldiameter pipes are usually referred to as *tubes.* Given this uncertainty, we will use more descriptive phrases (such as *a circular pipe* or *a rectangular duct*) whenever necessary to avoid any misunderstandings.

You have probably noticed that most fluids, especially liquids, are transported in *circular pipes.* This is because pipes with a circular cross section can withstand large pressure differences between the inside and the outside without undergoing significant distortion. *Noncircular pipes* are usually used in applications such as the heating and cooling systems of buildings where the pressure difference is relatively small, the manufacturing and installation costs are lower, and the available space is limited for ductwork (Fig.5.1).

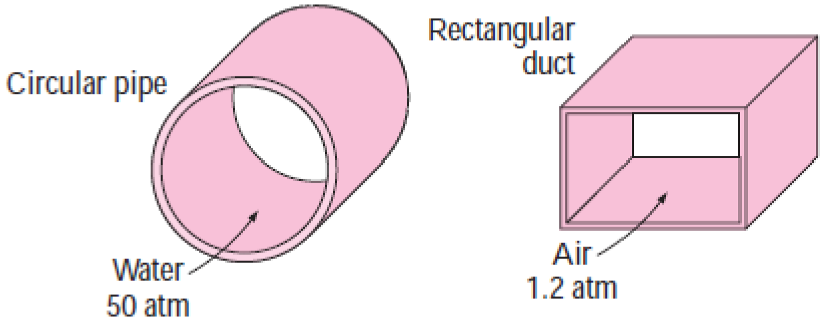

Figure 5.1. Circular pipes can withstand large pressure differences between the inside and the outside without undergoing any significant distortion, but noncircular pipes cannot

The fluid velocity in a pipe changes from *zero* at the surface because of the no-slip condition to a maximum at the pipe center. In fluid flow, it is convenient to work with an *average* velocity V_{avg}, which remains constant in incompressible flow when the cross-sectional area of the pipe is constant (Fig.5.2). The average velocity in heating and cooling applications may change somewhat because of changes in density with temperature. But, in practice, we evaluate the fluid properties at some average temperature and treat them as constants. The convenience of working with constant properties usually more than justifies the slight loss in accuracy.

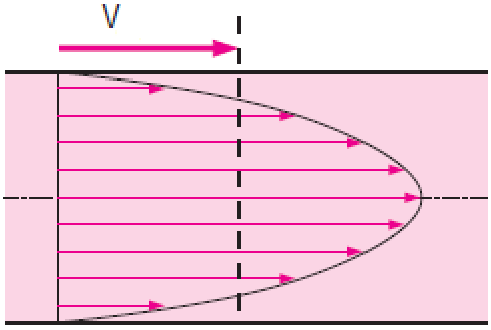

Figure 5.2. Average velocity *V* is defined as the average speed through a cross section. For fully developed laminar pipe flow, *V* is half of maximum velocity.

5.1 General Characteristics of Pipe Flow

Before we apply the various governing equations to pipe flow examples, we will discuss some of the basic concepts of pipe flow. With these ground rules established we can then proceed to formulate and solve various important flow problems.

Although not all conduits used to transport fluid from one location to another are round in cross section, most of the common ones are. These include typical water pipes, hydraulic hoses, and other conduits that are designed to withstand a considerable pressure difference across their walls without undue distortion of their shape. Typical conduits of noncircular cross section include heating and air conditioning ducts that are often of rectangular cross section. Normally the pressure difference between the inside and outside of these ducts is relatively small. Most of the basic principles involved are independent of the cross-sectional shape, although the details of the flow may be dependent on it. Unless otherwise specified, we will assume that the conduit is round, although we will show how to account for other shapes.

For all flows involved in this chapter, we assume that the pipe is completely filled with the fluid being transported as is shown in Fig.5.3*a*. Thus, we will not consider a concrete pipe through which rainwater flows without completely filling the pipe, as is shown in Fig.5.3*b*. The difference between open-channel flow and the pipe flow of this chapter is in the fundamental mechanism that drives the flow. For open-channel flow, gravity alone is the driving force—the water flows down a hill. For pipe flow, gravity may be important (the pipe need not be horizontal), but the main driving force is likely to be a pressure gradient along the pipe. If the pipe is not full, it is not possible to maintain this pressure difference, P_1-P_2.

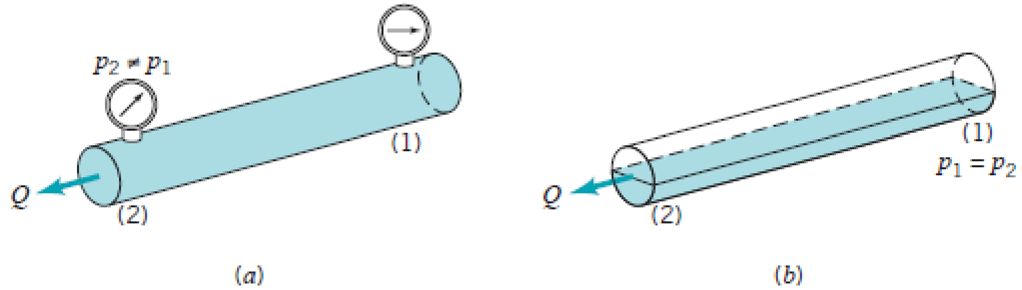

Figure 5.3. (*a*) Pipe flow. (*b*) Open-channel flow.

5.1.1. Laminar or Turbulent Flow

The flow of a fluid in a pipe may be laminar flow or it may be turbulent flow. Osborne Reynolds 11842–19122, a British scientist and mathematician, was the first to distinguish the difference between these two classifications of flow by using a simple apparatus as shown by the figure, which is a sketch of Reynolds' dye experiment. Reynolds injected dye into a pipe in which water flowed due to gravity. The entrance region of the pipe is depicted in Fig.5.4*a*. 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 flowrates" the dye streak (a streakline) will remain as a well-defined line as it flows along, with only slight blurring due to molecular diffusion of the dye into the surrounding water. For a somewhat larger "intermediate flowrate" 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 flowrates" the dye streak almost immediately becomes blurred and spreads across the entire pipe in a random fashion. These three characteristics, denoted as ***laminar***, ***transitional***, and ***turbulent*** flow, respectively, are illustrated in Fig. 5.4*b*.

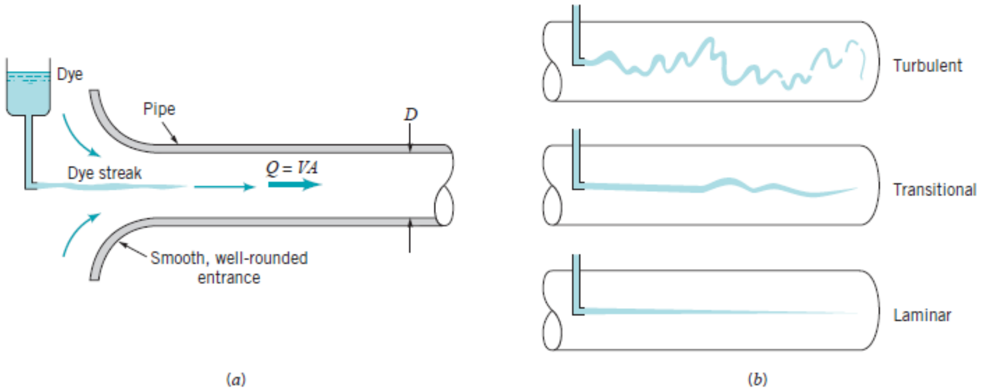

Figure 5.4. (*a*) Experiment to illustrate type of flow. (*b*) Typical dye streaks.

The curves shown in the below Fig.5.5 represent the *x* component of the velocity as a function of time at a point *A* in the flow. The random fluctuations of the turbulent flow (with the associated particle mixing) are what disperse the dye throughout the pipe and cause the blurred appearance illustrated in Fig. 5.5*b*. For laminar flow in a pipe there is only one component of velocity, $\boldsymbol{V} = u\hat{\boldsymbol{\imath}}$. For turbulent flow the predominant component of velocity is also along the pipe, but it is unsteady (random) and accompanied by random components normal to the pipe axis, $\boldsymbol{V} = u\hat{\boldsymbol{\imath}} + v\hat{\boldsymbol{\jmath}} + w\hat{\boldsymbol{k}}$. Such motion in a typical flow occurs too fast for our eyes to follow. Slow motion pictures of the flow can more clearly reveal the irregular, random, turbulent nature of the flow.

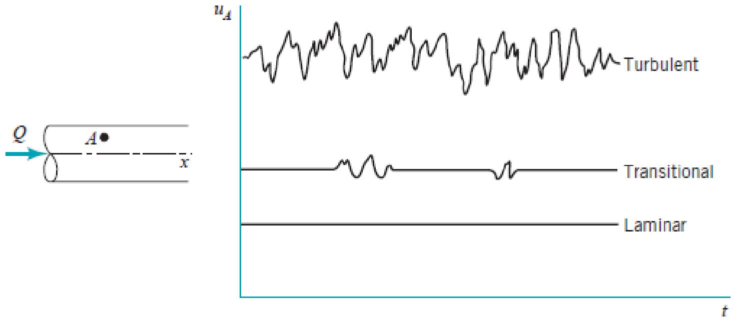

Figure 5.5. Time dependence of fluid velocity at a point.

The transition from laminar to turbulent flow depends on the ***geometry, surface roughness, flow velocity, surface temperature,*** **and** ***type of fluid,*** among other things. After exhaustive experiments in the 1880s, Osborne Reynolds discovered that the flow regime depends mainly on the ratio of *inertial forces* to *viscous forces* in the fluid. This ratio is called the ***Reynolds number*** and is expressed for internal flow in a circular pipe as

$$Re = \frac{Inertial\ forces}{Viscous\ forces} = \frac{VD}{\nu} = \frac{\rho VD}{\mu}$$

Where V is the average flow velocity (m/s), *D is the* characteristic length of the geometry (diameter in this case, in m), and $\nu = \mu / \rho$ is the kinematic viscosity of the fluid (m^2/s). Note that the Reynolds number is a *dimensionless* quantity. Also, kinematic viscosity has the unit m^2/s, and can be viewed as ***viscous diffusivity*** or ***diffusivity for momentum***.

The Reynolds number ranges 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 of the entrance region, and the like. For general engineering purposes (i.e., without undue precautions 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 turbulent if the Reynolds number is greater than approximately 4000. For Reynolds numbers between these two limits, (2100<Re<4000) the flow may switch between laminar and turbulent conditions in an apparently random fashion (transitional flow).

$Re \leq 2100 \rightarrow Laminar\ flow$
$2100 < Re < 4000 \rightarrow Transitional\ flow$
$Re \geq 4000 \rightarrow Turbulent\ flow$

5.1.2 Entrance Region and Fully 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* and is illustrated in Fig.5.6. It may be the first few feet of a pipe connected to a tank or the initial portion of a long run of a hot air duct coming from a furnace.

As is shown in Fig.5.6, the fluid typically enters the pipe with a nearly uniform velocity profile at section (1). As the fluid moves through the pipe, viscous effects cause it to stick to the pipe wall (the no-slip boundary condition). This is true whether the fluid is relatively inviscid air or a very viscous oil. Thus, a *boundary layer* in which viscous effects are important is produced along the pipe wall such that the initial velocity profile changes with distance along the pipe, *x*, until the fluid reaches the end of the entrance length, section (2), beyond which the velocity profile does not vary with *x*.

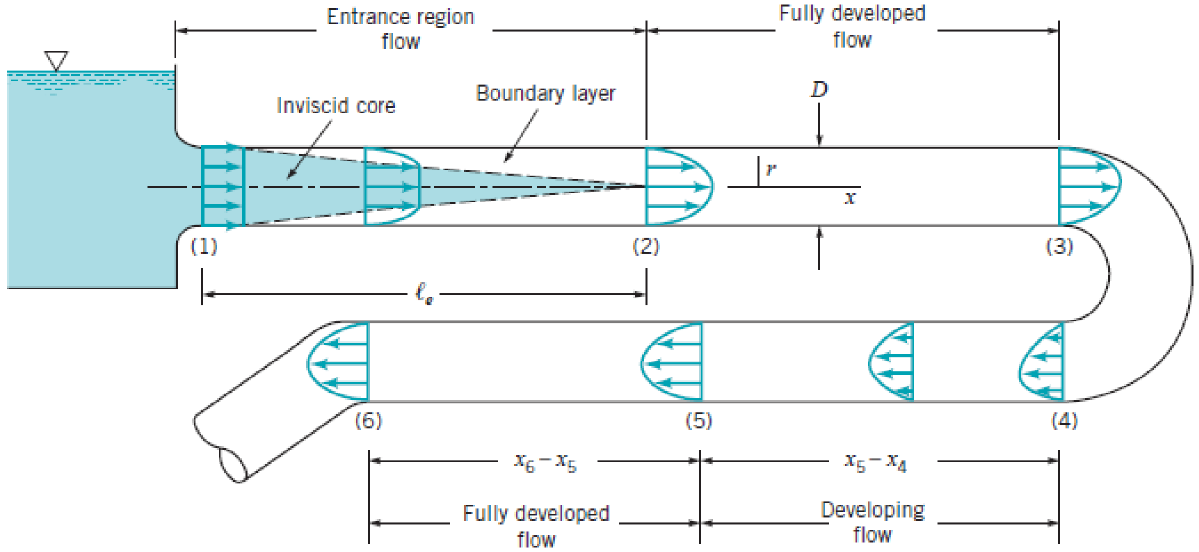

Figure 5.6. Entrance region, developing flow, and fully developed flow in a pipe system.

The boundary layer has grown in thickness to completely fill the pipe. Viscous effects are of considerable importance within the boundary layer. For fluid outside the boundary layer [within the *inviscid 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, L_e. As with many other properties of pipe flow, the dimensionless ***entrance length,*** L_e/D correlates quite well with the Reynolds number. Typical entrance lengths are given by

$Le/D=0.06\ Re$ for laminar flow

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

For very low Reynolds number flows the entrance length can be quite short ($Le=0.6D$ *if* $Re=10$) if whereas for large Reynolds number flows it may take a length equal to many pipe diameters before the end of the entrance region is reached ($Le=120D$ *for* $Re=2000$). For many practical engineering problems, $20D < Le < 30D$ for $10^4 < \mathrm{Re} < 10^5$.

Calculation of the velocity profile and pressure distribution within the entrance region is quite complex. However, once the fluid reaches the end of the entrance region, section (2) of Fig.5.6, the flow is simpler to describe because the velocity is a function of only the distance from the pipe centerline, r, and independent of x. This is true until the character of the pipe changes in some way, such as a change in diameter, or the fluid flows through a bend, valve, or some other component at section (3). The flow between (2) and (3) is termed ***fully developed flow.*** Beyond the interruption of the fully developed flow [at section (4)], the flow gradually begins its return to its fully developed character [section (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 fully developed flow compared with the developing flow length $[(x_3 - x_2) \gg L_e \ and \ (x_6 - x_5) \gg (x_5 - x_4)]$. In other cases, the distances between one component (bend, tee, valve, etc.) of the pipe system and the next component is so short that fully developed flow is never achieved.