4

Air Pollution Physics

A thorough understanding of air pollution begins with physics. It is how we understand matter and energy. As such, it provides the basis for chemistry. So, how things move and how efficiently energy is transferred among compartments lie at the heart of understanding air pollution. This is not only true for air pollution control technologies and other engineered systems but also for how a pollutant will affect a receptor. Human health effects and exposure assessments require that the movement of and changes to contaminants be understood. This requires a solid grounding in the physical and chemical principles covered in this part. Likewise, ecological risk assessments require an understanding of physicochemical, thermodynamic, hydrological, and aerodynamic concepts to appreciate how chemical nutrients and contaminants cycle through the environment, how physical changes may impact receptors, and the many possible ways that the environment is put at risk. In a very basic way, we must consider the first principles to have rigorous environmental assessments and to give reliable information to the engineers and decision makers who will respond to health and ecological risks. Good policy stands on quality science.

Let us note a few areas of environmental risk that are heavily dependent upon physics. First, energy is often described as a system's capacity to do work, so getting things done in the environment is really an expression of how efficiently energy is transformed from one form to another. Energy and matter relationships determine how things move in the environment. That is why we begin our discussion of applied physics with environmental transport. The physical movement of contaminants among environmental *compartments* is central to risk assessment. After a contaminant is released, physical processes will go to work on transporting the contaminant and allow for *receptors* (like people and ecosystems) to be exposed. Transport is one of the two processes (the other is *transformation*) that determine a contaminant's *fate* in the environment. Figure 4.1 shows the major steps needed to study a contaminant as it moves through the environment.

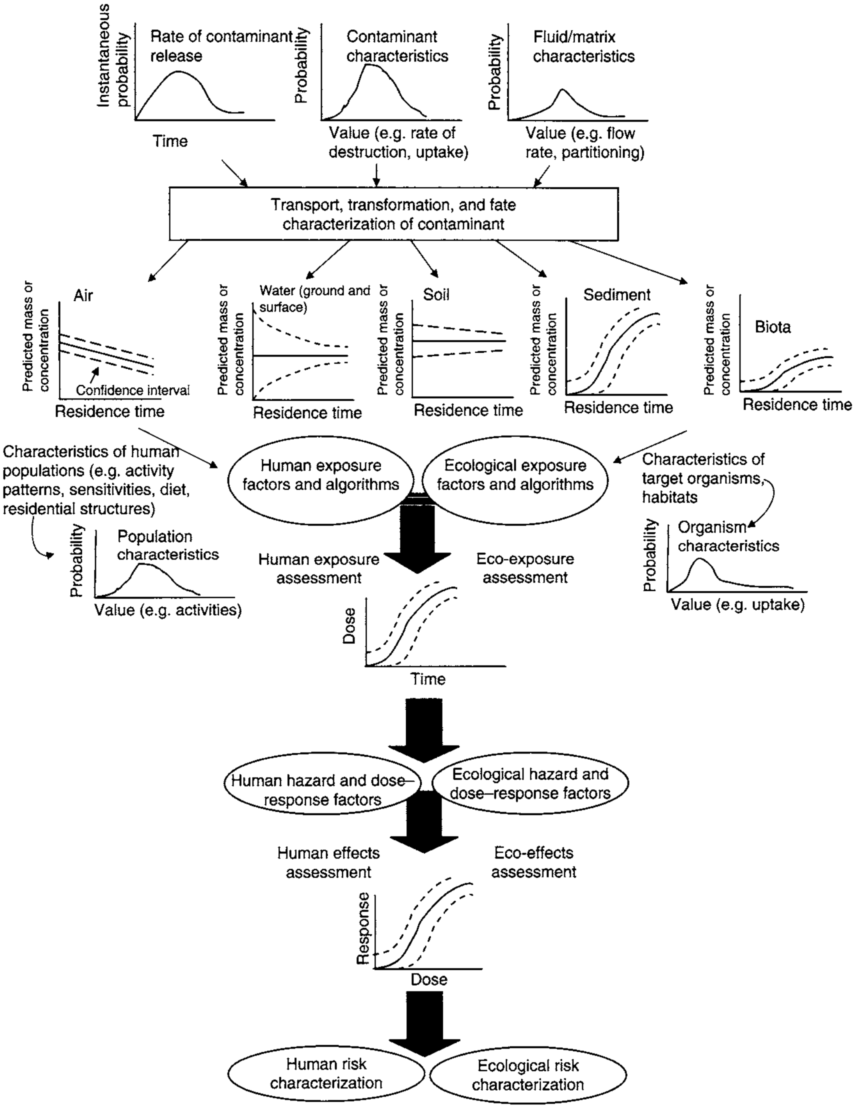

Fig. 4.1. Importance of transport, transformation, and fate processes to human and ecological exposure and risk assessments. Source for ecological exposure components: Suter, G., Predictive risk assessment of chemicals, in *Ecological Risk Assessment* (Suter, G., ed.), Lewis Publishers, Chelsea, MI, 1993.

Scientists and engineers are particularly interested in the role of fluids in air pollution. A fluid is a substance that cannot support a shearing force, so fluids take the form of their containing vessel. The obvious fluid that is important at all scales, from molecular to global, is the air itself. Next, arguably, is water. However, fluid properties, statics, and dynamics are involved in every aspect of air pollution, from characterizing emissions from a source to the biological response to the released pollutants. To identify a hazard and dose–response associated with the chemical, the fluid properties must be understood. For example, if a contaminant's fluid properties make it insoluble in water and blood, then the target tissues may be more likely to be the lipids. If a chemical is easily absorbed, the hazard may be higher. However, if it does not change phases under certain cellular conditions, it could be more or less toxic, depending on the organ.

In determining exposures, in addition to the transport phenomena mentioned earlier, the fluid properties of a pollutant is a crucial factor as to where the contaminant is likely to be found in the environment (e.g. in the air as a vapor, sorbed to a particle, dissolved in water, or taken up by biota).

Physics and chemistry are interrelated; in fact, for air pollution it is arguably best to refer to physicochemical processes. The literature is ripe with lists of chemical compounds that have been associated with diseases. Much of risk assessment follows the toxicological paradigm (which is really an enhancement of the pharmacological paradigm), wherein chemicals are considered from a dose–response perspective (see Fig. 4.1). Indeed, air pollution exposure assessments rely on analytical chemistry in determining the presence and quantity of a chemical contaminant in the environment. Also, toxicology begins with an understanding of the chemical characteristics of an agent, followed by investigations of how the agent changes after release and up to the adverse effect. So, whether the chemistry is inorganic or organic, whether it is induced, mediated, or complemented by biological processes or is simply abiotic chemistry, and whether it is applied at the molecular or global scale, every risk assessment, every intervention, and every engineering activity is a chemical expression.

Several of the topics considered in transport provide a transition from physics to atmospheric chemistry; especially phase partitioning and fluid properties. In fact, no air pollution chemistry discussion is complete without discussions of mass balance and partitioning.

I. MECHANICS OF AIR POLLUTION

Mechanics is the field of physics concerned with the motion and the equilibrium of bodies within particular frames of reference. Air pollution scientists make use of the mechanical principles in practically every aspect of pollution, from the movement of fluids that carry contaminants to the forces within substances that affect their properties to the relationships between matter and energy within organisms and ecosystems. Engineering mechanics is important because it includes statics and dynamics. Fluid mechanics is a particularly important branch of the mechanics of air pollution.

Statics is the branch of mechanics that is concerned with bodies at rest with relation to some frame of reference, with the forces between the bodies, and with the equilibrium of the system. It addresses rigid bodies that are at rest or moving with constant velocity. Hydrostatics is a branch of statics that is essential to environmental science and engineering in that it is concerned with the equilibrium of fluids (liquids and gases) and their stationary interactions with solid bodies, such as pressure. While many fluids are considered by environmental assessments, the principal fluids are water and air.

Dynamics is the branch of mechanics that deals with forces that change or move bodies. It is concerned with accelerated motion of bodies. It is an especially important science and engineering discipline because it is fundamental to understanding the movement of contaminants through the environment. Dynamics is sometimes used synonymously with kinetics. However, we will use the engineering approach and treat kinetics as one of the two branches of dynamics, with the other being kinematics. Dynamics combines the properties of the fluid and the means by which it moves. This means that the continuum fluid mechanics varies by whether the fluid is viscous or inviscid, compressible or incompressible, and whether flow is laminar or turbulent. For example, the properties of the two principal environmental fluids, i.e. water in an aquifer and an air mass in the troposphere, are shown in Table 4.1. Thus, in air pollution mechanics, turbulent systems are quite common. However, within smaller systems, such as control technologies, laminar conditions can be prominent.

Dynamics is divided into kinematics and kinetics. Kinematics is concerned with the study of a body in motion independent of forces acting on the body. That is, kinematics is the branch of mechanics concerned with motion of bodies with reference to force or mass. This is accomplished by studying the geometry of motion irrespective of what is causing the motion. Therefore, kinematics relates position, velocity, acceleration, and time.

Aerodynamics and hydrodynamics are the important branches of environmental mechanics. Both are concerned with deformable bodies and with the motion of fluids. Therefore, they provide an important underlying aspect of contaminant transport and movements of fluids, and consider fluid properties

TABLE 4.1

Contrasts Between Plume in Ground Water and Atmosphere

	Ground water plume	Air mass plume
General flow type	Laminar	Turbulent
Compressibility	Incompressible	Compressible
Viscosity	Low viscosity (1×10^{-3} kg m^{-1} s^{-1} at 288°K)	Very low viscosity (1.781×10^{-5} kg m^{-1} s^{-1} at 288°K)

such as compressibility and viscosity. These are key to understanding movement of contaminants within plumes, flows in vents and pipes, and design of air pollution control systems.

Kinetics is the study of motion and the forces that cause motion. This includes analyzing force and mass as they relate to translational motion. Kinetics also considers the relationship between torque and moment of inertia for rotational motion.

A key concept for environmental dynamics is that of linear momentum, the product of mass and velocity. A body's momentum is conserved unless an external force acts upon a body. Kinetics is based on Newton's *first law of motion*, which states that a body will remain in a state of rest or will continue to move with constant velocity unless an unbalanced external force acts on it. Stated as the *law of conservation of momentum*, linear momentum is unchanged if no unbalanced forces act on a body. Or, if the resultant external force acting on a body is zero, the linear momentum of the body is constant.

Kinetics is also based upon Newton's *second law of motion*, which states that the acceleration of a body is directly proportional to the force acting upon that body, and inversely proportional to the body's mass. The direction of acceleration is the same as the force of direction. The equation for the second law is:

$$F = \frac{\mathrm{d}p}{\mathrm{d}t} \tag{4.1}$$

where p is the momentum.

Newton's *third law of motion* states that for every acting force between two bodies, there is an equal but opposite reacting force on the same line of action, or:

$$F_{\text{reacting}} = -F_{\text{acting}} \tag{4.2}$$

Another force that is important to environmental systems is *friction*, which is a force that always resists motion or an impending motion. Friction acts parallel to the contacting surfaces. When bodies come into contact with one another, friction acts in the direction opposite to that that is bringing the objects into contact.

II. FLUID PROPERTIES

Air pollutants may move within one environmental compartment, such as a source within a home. Most often, however, pollutants move among numerous compartments, such as when a contaminant moves from the source to the atmosphere, until it is deposited to the soil and surface waters, where it is taken up by plants, and eaten by animals.[1]

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[1] While this book strives to compartmentalize the science discussions among physics, chemistry, and biology, complex topics like transport require that all three of the sciences be considered together. So, while the focus and language of this chapter is predominantly on physical transport, it would be wise to interject chemical and biological topics to explain the concepts properly.

The general behavior of contaminants after they are released is shown in Fig. 4.2. The movement of pollutants is known as *transport*. This is half of the often cited duo of environmental "fate and transport." *Fate* is an expression of what contaminant becomes after all the physical, chemical, and biological processes of the environment have acted. It is the ultimate site a pollutant

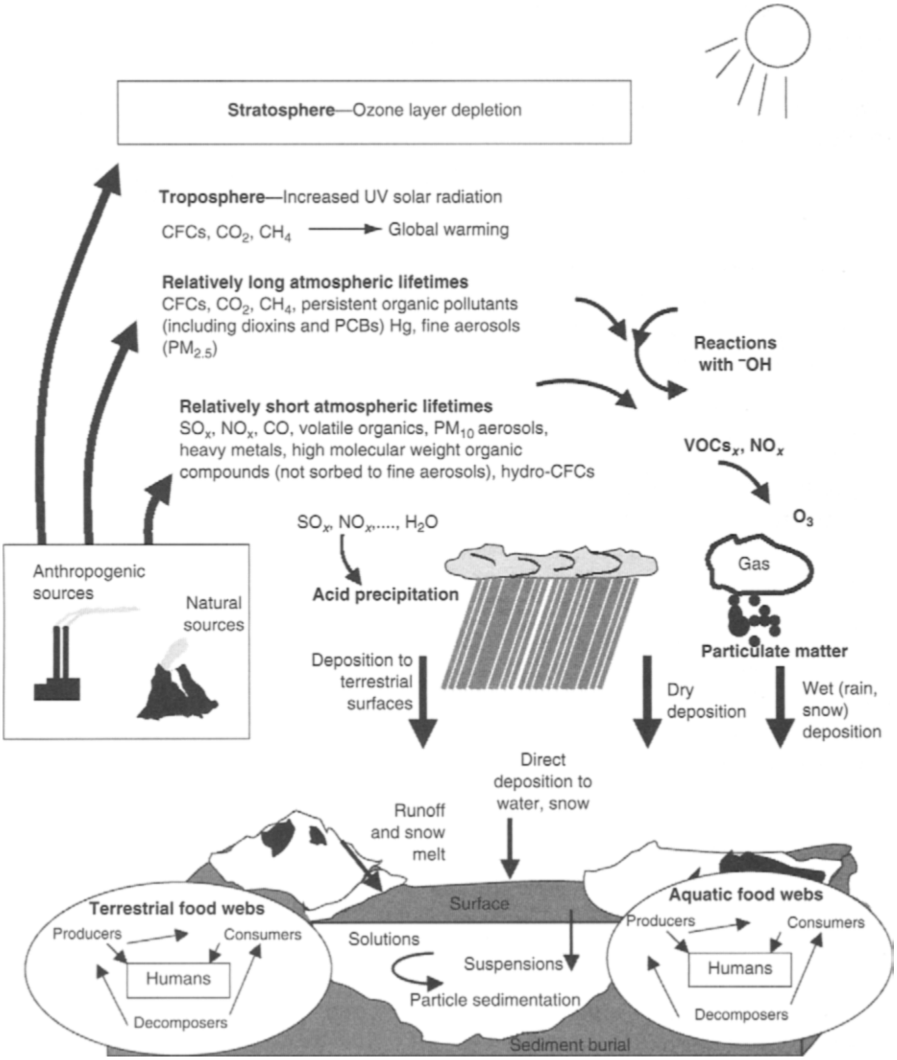

Fig. 4.2. The physical movement and accumulation of contaminants after release. *Sources*: Commission for Environmental Cooperation of North America, 2002, The Sound Management of Chemicals (SMOC) Initiative of the Commission for Environmental Cooperation of North America: Overview and Update, Montreal, Canada; Adapted in Vallero, D.A., *Environmental Contaminants: Assessment and Control*, Elsevier Academic Press, Burlington, MA, 2004.

after its release. The pollutant will undergo numerous changes in location and form before reaching its fate. Throughout the contaminant's journey it will be physically transported and undergo coincidental chemical processes, known as *transformations*, such as photochemical and biochemical reactions.[2]

Physical transport is influenced by the kinematics and mechanics of fluids. In addition, it is important to identify when these processes reach equilibrium, such as when a chemical is sequestered and stored. Fate is often described according to environmental media or compartments.

Understanding air pollutant transport begins with the characteristics of environmental fluids. A fluid is a collective term that includes all liquids and gases. A liquid is matter that is composed of molecules that move freely among themselves without separating from each other. A gas is matter composed of molecules that move freely and are infinitely able to occupy the space with which they are contained at a constant temperature. A fluid is a substance that will deform continuously upon the application of a shear stress; i.e., a stress in which the material on one side of a surface pushes on the material on the other side of the surface with a force parallel to the surface.

Fluids are generally divided into two types: *ideal* and *real*. The former has zero viscosity and, thus, no resistance to shear (explained below). An ideal fluid is incompressible and flows with uniform velocity distributions. It also has no friction between moving layers and no turbulence (i.e. eddy currents). On the contrary, a real fluid has finite viscosity, has non-uniform velocity distributions, is compressible, and experiences friction and turbulence. Real fluids are further subdivided according to their viscosities. A *Newtonian fluid* is one that has a constant viscosity at all shear rates at a constant temperature and pressure. Water and most solvents are Newtonian fluids. However, environmental engineers are confronted with non-Newtonian fluids, i.e. those with viscosities not constant at all shear rates. Sites contaminated with drilling fluids and oils have large quantities of non-Newtonian fluids onsite.

Physicists use the term "particle" to mean a theoretical point that has a rest-mass and location, but no geometric extension. We can observe this particle as it moves within the fluid as a representation of where that portion of the fluid is going and at what velocity. Another important concept is that of the *control volume*, which is an arbitrary region in space that is defined by boundaries. The boundaries may be either stationary or moving. The control volume is used to determine how much material and at what rate the material is moving through the air, water, or soil. The third concept, which is included in the definition of a fluid, is *stress*. The forces acting on a fluid may be *body forces* or *surface forces*. The former are forces that act on every particle within the fluid, occurring without actually making physical contact, such as

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[2] Fate may also include some remediation reactions, such as thermal and mechanical separation processes, but in discussions of fate and transport, the reactions are usually those that occur in the ambient environment. The treatment and control processes usually fall under the category of environmental engineering.

gravitation force. The latter are forces that are applied directly to the fluid's surface by physical contact.

Stress represents the total force per unit area acting on a fluid at any point within the fluid volume. So, stress at any point P is

$$\sigma(P) = \lim_{\delta A \to 0} \frac{\delta F}{\delta A} \tag{4.3}$$

where $\sigma(P)$ is the vector stress at point P, δA is the infinitesimal area at point P, and δF is the force acting on δA.

Fluid properties are characteristics of the fluid that are used to predict how the fluid will react when subjected to applied forces. If a fluid is considered to be infinitely divisible, that is, it is made up of many molecules that are constantly in motion and colliding with one another, this fluid is in *continuum*. That is, a fluid acts as though it has no holes or voids, meaning its properties are continuous (i.e. temperature, volume, and pressure fields are continuous). If we make the assumption that a fluid is a continuum we can consider the fluid's properties to be functions of position and time. So, we can represent the fluid properties as two fields. The density field shows:

$$\rho = \rho(x, y, z, t) \tag{4.4}$$

where ρ is the density of the fluid, x, y, z are the coordinates in space, and t is the time.

The other fluid field is the velocity field:

$$\vec{v} = \vec{v}(x, y, z, t) \tag{4.5}$$

Thus, if the fluid properties and the flow characteristics at each position do not vary with time, the fluid is said to be at *steady flow*:

$$\rho = \rho(x, y, z) \text{ or } \frac{\partial \rho}{\partial t} = 0 \tag{4.6}$$

and

$$\vec{v} = \vec{v}(x, y, z) \text{ or } \frac{\partial \vec{v}}{\partial t} = 0 \tag{4.7}$$

Conversely, a *time-dependent flow* is considered to be an *unsteady flow*. Any flow with unchanging magnitude and direction of the velocity vector $\vec{v}$ is considered to be a *uniform flow*.

Fluids, then, can be classified according to observable physical characteristics of flow fields. A continuum fluid mechanics classification is shown in Fig. 4.3. Laminar flow is in layers, while turbulent flow has random movements of fluid particles in all directions. In incompressible flow, the variations in density are assumed to be constant, while the compressible flow has density variations, which must be included in flow calculations. Viscous flows must account for viscosity while inviscid flows assume viscosity is zero.

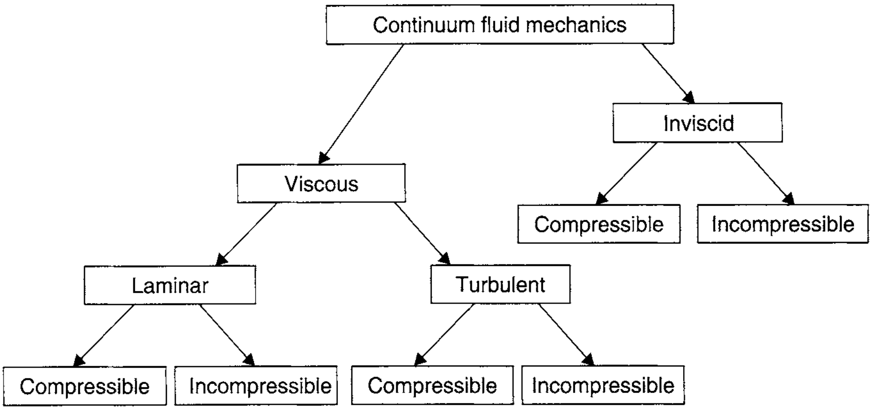


Fig. 4.3. Classification of Fluids Based on Continuum Fluid Mechanics. *Source*: Research and Education Association, *The Essentials of Fluid Mechanics and Dynamics I*. REA, Piscataway, NJ, 1987.

The velocity field is very important in environmental modeling, especially in modeling plumes in the atmosphere and in groundwater, since the velocity field is a way to characterize the motion of fluid particles and provides the means for computing these motions. The velocity field may be described mathematically using Eq. (4.5). This is known as the *Eularian* viewpoint.

Another way to characterize the fluid movement (i.e. flow) is to follow the particle (sometimes referred to as a "parcel") as it moves, using time functions that correspond to each particle as shown in Fig. 4.4. This *random walk* of the particle provides what is known as the *Lagrangian* viewpoint, which is expressed mathematically as:

$$\vec{v} = [x(t), y(t), z(t)] \tag{4.8}$$

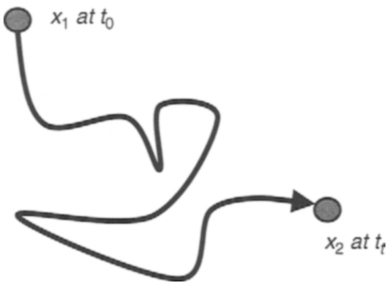


Fig. 4.4. Random walk representing the movement of a particle; i.e. a hypothetical point that is moving in a random path during time interval ($t_0 - t_t$). This is the theoretical basis for Lagrangian air plume models.

A Lagrangian plume model characterizes the plume by calculating the air dispersion from statistics of the trajectories of a large number of the particles (enough to represent the whole plume).

Velocity The time rate of change of a fluid particle's position in space is the fluid velocity (V). This is a vector field quantity. Speed (V) is the magnitude of the vector velocity V at some given point in the fluid, and average speed ($\bar{V}$) is the mean fluid speed through a control volume's surface. Therefore, velocity is a vector quantity (magnitude and direction), while speed is a scalar quantity (magnitude only). The standard units of velocity and speed are meter per second ($\mathrm{m\,s^{-1}}$).

Obviously, velocity is important to determine pollution, such as mixing rates after a pollutant is emitted into a plume. The distinction between velocity and speed is seldom made in air pollution.

Pressure A force per unit area is pressure (p):

$$p = \frac{F}{A} \tag{4.9}$$

So, p is a type of stress that is exerted uniformly in all directions. It is common to use pressure instead of force to describe the factors that influence the behavior of fluids. The standard unit of p is the Pascal (P), which is equal to $1\,\mathrm{N\,m^{-2}}$. Therefore, pressure will vary when the area varies, as shown in Fig. 4.5. In this example, the same weight (force) over different areas leads to different pressures, much higher pressure when the same force is distributed over a smaller area.

For a liquid at rest, the medium is considered to be a continuous distribution of matter. However, when considering p for a gas, the pressure is an average of the forces against as the vessel walls (i.e. gas pressure). Fluid pressure is a measure of energy per unit volume per the *Bernoulli equation*, which states that the static pressure in the flow plus one half of the density times

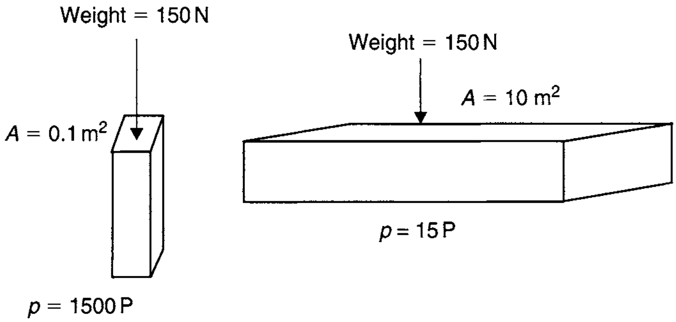


Fig. 4.5. Difference in pressure with same weight over different areas.

the velocity squared is equal to a constant throughout the flow, referred to as the total pressure of the flow:

$$p + \tfrac{1}{2}pV^2 + pgh = \text{constant} \tag{4.10}$$

where p is the pressure, V is the fluid velocity, h is the elevation, and g is the gravitational acceleration.

This also means that, in keeping with the conservation of energy principle, a flowing fluid will maintain the energy, but velocity and pressure can change. In fact, velocity and pressure will compensate for each other to adhere to the conservation principle, as stated in the Bernoulli equation:

$$p_1 + \tfrac{1}{2}pV_1^2 + pgh_1 = p_2 + \tfrac{1}{2}pV_2^2 + pgh_2 \tag{4.11}$$

This is shown graphically in Fig. 4.6. The so-called "Bernoulli effect" occurs when increased fluid speed leads to decreased internal pressure.

In environmental applications, fluid pressure is measured against two references: *zero pressure* and *atmospheric pressure. Absolute pressure* is compared to true zero pressure and *gage pressure* is reported in reference to atmospheric pressure. To be able to tell which type of pressure is reported, the letter "a" and the letter "g" are added to units to designate whether the pressure is absolute or gage, respectively. So, it is common to see pounds per square inch designated as "psia" or inches of water as "in wg". If no letter is designated, the pressure can be assumed to be absolute pressure.

When a gage measurement is taken, and the actual atmospheric pressure is known, absolute and gage pressure are related:

$$p_{\text{absolute}} = p_{\text{gage}} + p_{\text{atmospheric}} \tag{4.12}$$

Barometric and atmospheric pressure are synonymous. A negative gage pressure implies a *vacuum* measurement. A reported vacuum quantity is to be subtracted from the atmospheric pressure. So, when a piece of equipment

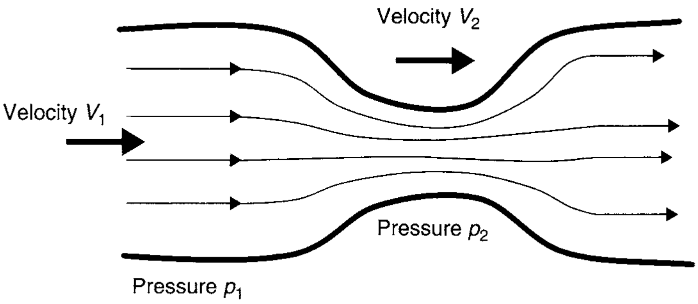


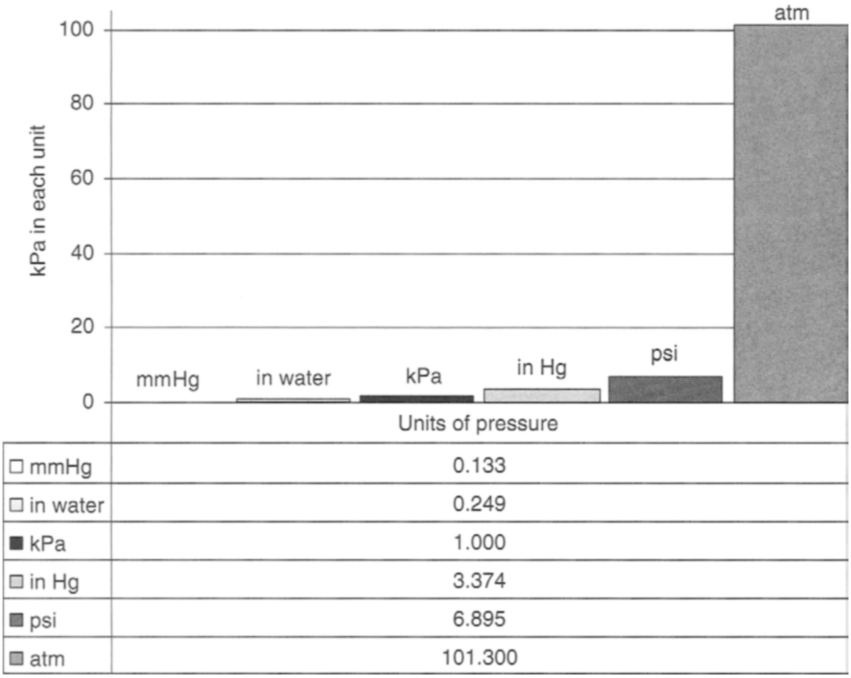
Fig. 4.6. Bernoulli principle and the effect of relationship between pressure, energy, area, and velocity. As the cross-sectional area of flow decreases, the velocity increases and the pressure decreases.

is operating with 20 kPa vacuum, the absolute pressure is 101.3 kPa − 20 kPa = 81.3 kPa. (*Note*: The standard atmospheric pressure = 101.3 kPa = 1.013 bars). Thus, the relationship between vacuums, which are always given as positive numbers, and absolute pressure is:

$$p_{\text{absolute}} = p_{\text{atmospheric}} - p_{\text{vacuum}} \tag{4.13}$$

Pressure is used throughout this text, as well as in any discussion of physics, chemistry, and biology. Numerous units are used. The preferred unit in this book is the kPa, since the standard metric unit of pressure is the Pascal, which is quite small. See Fig. 4.7 for a comparison of relative size of pressure units commonly used in environmental assessments, research studies, and textbooks.

Acceleration Any discussion of potential and kinetic energies includes acceleration due to gravity. In many ways, it seems that acceleration was a major reason for Isaac Newton's need to develop the calculus.[3] Renaissance



□ mmHg	0.133
□ in water	0.249
■ kPa	1.000
□ in Hg	3.374
■ psi	6.895
▨ atm	101.300

Fig. 4.7. Comparison of the size of pressure units.

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[3] Newton simultaneously invented the calculus with Gottfried Wilhelm Leibnitz (1646–1716) in the seventeenth century. Both are credited with devising the symbolism and the system of rules for computing derivatives and integrals, but their notation and emphases differed. A debate rages on who did what first, but both of these giants had good reason to revise the language of science; i.e., mathematics, to explain motion.

scientists (Galileo, Kepler, *et al.*) may well have understood the concept of acceleration, but needed the structure brought by the calculus. The calculus is the mathematics of change, which is what acceleration is all about.

Acceleration is the time rate of change in the velocity of a fluid particle. In terms of calculus, it is a second derivative. That is, it is the derivative of the velocity function. And a derivative of a function is itself a function, giving its rate of change. This explains why the second derivative must be a function showing the rate of change of the rate of change. This is obvious when one looks at the units of acceleration: length per time per time ($\mathrm{m\,s^{-2}}$).

FLUID ACCELERATION EXAMPLE

If a fluid is moving at the constant velocity of $4\,\mathrm{m\,s^{-1}}$, what is the rate of change of the velocity? What is the second derivative of the fluid's movement?

The function $s = f(t)$ shows the distance the fluid has moved (s) after t seconds. If the fluid is traveling at $4\,\mathrm{m\,s^{-1}}$, then it must travel 4 meters for each second, or $4t$ meters after t seconds. The rate of change of distance (how fast the distance is changing) is the speed. We know that this is $4\,\mathrm{m\,s^{-1}}$. So:

$$s = f(t) = 4t \tag{4.14}$$

and

$$\mathrm{d}s/\mathrm{d}t = f'(t) = 4$$

In acceleration, we are interested in the rate of change of the rate of change. This is the rate of change of the fluid velocity. Since the fluid is moving at constant velocity, it is not accelerating.

So acceleration = 0.

This is another way of saying that when we differentiate for a second time (called the *second derivative*), we find it is zero.

Displacement, Velocity and Acceleration The three concepts just discussed can be combined to describe fluid movement. If we are given the function $f(t)$ as the displacement of a particle in the fluid at time t, the derivative of this function $f'(t)$ represents the velocity. The second derivative $f''(t)$ represents the acceleration of the particle at time t:

$$s = f(t) \tag{4.15}$$

$$v = \mathrm{d}s/\mathrm{d}t = f'(t) \tag{4.16}$$

$$a = \mathrm{d}^2s/\mathrm{d}t^2 = f''(t) \tag{4.17}$$

AIR POLLUTION MATHEMATICS: STATIONARY POINTS IN A FLUID

The derivative of a function can be described graphically (see Fig. 4.8). If the derivative is zero, the function is flat and must therefore reside where the graph is turning. We are able to identify the turning points of a function by differentiating and setting the derivative equal to zero. Turning points may be of three types: minima (Fig. 4.8(a)), maxima (Fig. 4.8(b)) and points of inflexion (Fig. 4.8(c)). The graph shows how the derivatives are changing around each of these stationary points.

Near the point where the derivative is changing from negative to positive, it is increasing. In other words the rate of change in velocity is positive. So, the derivative of the derivative; i.e., second derivative, must be positive. When the second derivative is positive at a given turning point, this is the minimum point. Likewise, at the maximum negative to positive means that the derivative is decreasing; i.e., the rate of change is negative. This means when the second derivative is negative at a given turning point, this must be a maximum point.

At the inflection points, the rate of change is neither positive nor negative; i.e., the rate of change is zero. Keep in mind that zero is also a possible value for the second derivative at a maximum or minimum.

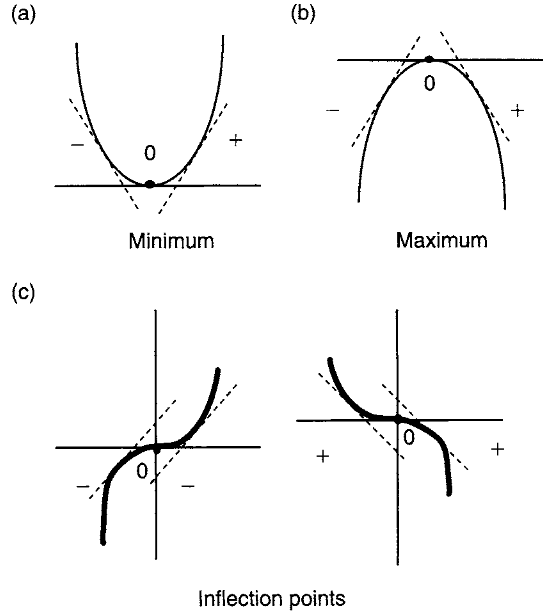

Fig. 4.8. Stationary points important to displacement, velocity, and acceleration of particles in a fluid.

Density The relationship between mass and volume is important in both environmental physics and chemistry, and is a fundamental property of fluids. The density (ρ) of a fluid is defined as its mass per unit volume. Its metric units are $\mathrm{kg\,m^{-3}}$. The density of an ideal gas is found using the specific gas constant and applying the ideal gas law:

$$\rho = p(RT) - 1 \tag{4.18}$$

where p is the gas pressure, R is the specific gas constant, and T is the absolute temperature.

So, the specific gas constant must be known to calculate gas density. For example, the R for air is $287\,\mathrm{J\,kg^{-1}\,K^{-1}}$. The specific gas constant for methane (R_{CH_4}) is $518\,\mathrm{J\,kg^{-1}\,K^{-1}}$.

Density is a very important fluid property for environmental situations. For example, a first responder must know the density of substances in an emergency situation. If a substance is burning, whether it is of greater or lesser density than water will be one of the factors on how to extinguish the fire. If the substance is less dense than water, the water will be more likely to settle below the layer of water, making water a poor choice for fighting the fire. So, any flammable substance with a density less than water (see Table 4.2), such as benzene or acetone, will require fire-extinguishing substances other than water. For substances heavier than water, like carbon disulfide, water may be a good choice.

TABLE 4.2

Densities of Selective Fluids Important in Air Pollution Science and Engineering

Fluid	Density ($\mathrm{kg\,m^{-3}}$) at 20°C unless otherwise noted
Air at standard temperature and pressure (STP) = 0°C and $101.3\,\mathrm{N\,m^{-2}}$	1.29
Air at 21°C	1.20
Ammonia	602
Diethyl ether	740
Ethanol	790
Acetone	791
Gasoline	700
Kerosene	820
Turpentine	870
Benzene	879
Pure water	1000
Seawater	1025
Carbon disulfide	1274
Chloroform	1489
Tetrachloromethane (carbon tetrachloride)	1595
Lead (Pb)	11 340
Mercury (Hg)	13 600

UNITS IN HANDBOOKS AND REFERENCE MANUALS

Standardization is important in air pollution science and engineering, but in the "real world," information is reported in many different formats. In fact, engineers seem to resist the use of SI units more than their colleagues in the basic sciences. This may, at least in part, be due to the historic inertia of engineering, where many equations were derived from English units. When an equation is based on one set of units and is only reported in those units, it can take much effort to convert them to SI units. Exponents in many water quality, water supply, and sludge equations have been empirically derived from studies that applied English units.

Some equations may use either English or SI units, such as the commonly used Hazen–Williams formula for mean velocity flow (v) in pressure pipes is:

$$v = 1.318C \cdot r^{0.63} \cdot s^{0.54} \tag{4.19}$$

where r is the hydraulic radius in feet or meters, s is the slope of the hydraulic grade line (head divided by length), and C is the friction coefficient (a function of pipe roughness).

The exponents apply without regard to units. Other formulae, however, require that a specific set of units be used. An example is the fundamental equation for kinetic energy. Two different equations are needed when using either the SI system or the English system, which requires the gravitation conversion constant (g_c) in the denominator. These are, respectively:

$$E_{\text{kinetic}} = \frac{mv^2}{2} \tag{4.20}$$

$$E_{\text{kinetic}} = \frac{mv^2}{2g_c} \text{(in ft-lbf)} \tag{4.21}$$

Two other important physical equations, potential energy and pressure require the insertion of their denominators:

$$E_{\text{potential}} = \frac{mgz}{g_c} \text{(in ft-lbf)} \tag{4.22}$$

$$p = \frac{\rho g h}{g_c} \text{(in ft-lbf ft}^{-2}\text{)} \tag{4.23}$$

where g is the gravitational acceleration, ρ is density, and h is the height.

With this in mind, it sometimes better to simply apply the formulae using English units and convert to metric or SI units following the calculation. In other words, rather than try to change the exponent or coefficient to address the difference in feet and meters, just use the units called for in the empirically derived equation. After completing the calculation, convert the answer to the correct units. This may seem contrary to the need to standardize units, but it may save time and effort in the long run. Either way, it is mathematically acceptable dimension analysis.

Another variation in units is how coefficients and constants are reported. For example, the octanol-water coefficient seems to be reported more often as $\log K_{ow}$ than simply as K_{ow}. This is usually because the ranges of K_{ow} values can be so large. One compound may have a coefficient of 0.001, while another has one of 1000. Thus, it may be more manageable to report the $\log K_{ow}$ values as -3 and 3 respectively.

Further, chemists and engineers are comfortable with the "*p*" notation as representative of the negative log. This could be because *p*H and *p*OH are common parameters. So, one may see the negative logarithm used with units in handbooks. For example, vapor pressure is sometimes reported as a negative log.

Therefore, examples and problems in handbooks and reference manuals make use of several different units as they are encountered in the environmental literature.

Specific volume The reciprocal of a substance's density is known as its specific volume (v). This is the volume occupied by a unit mass of a fluid. The units of v are reciprocal density units ($m^3\,kg^{-1}$). Stated mathematically, this is:

$$v = \rho^{-1} \tag{4.24}$$

Specific weight The weight of a fluid per its volume is known as specific weight (γ). Civil engineers sometimes use the term interchangeably with density. A substance's γ is not an absolute fluid property because it depends on the fluid itself and the local gravitational force:

$$\gamma = g\rho \tag{4.25}$$

The units are the same as those for density; e.g. $kg\,m^{-3}$.

Mole Fraction In a composition of a fluid made up of two or more substances (A, B, C, …), the mole fraction (x_A, x_B, x_C, …) is number of moles of each substance divided by the total number of moles for the whole fluid:

$$x_A = \frac{n_A}{n_A + n_B + n_C + \dots} \tag{4.26}$$

The mole fraction value is always between 0 and 1. The mole fraction may be converted to mole percent as:

$$x_{A\%} = x_A \times 100 \tag{4.27}$$

For gases, the mole fraction is the same as the volumetric fraction of each gas in a mixture of more than one gas.

Mole Fraction Example

112 g of $MgCl_2$ are dissolved in 1 L of water. The density of this solution is 1.089 g cm^{-3}. What is the mole fraction of $MgCl_2$ in the solution at standard temperature and pressure.

Solution

The number of moles of $MgCl_2$ is determined from its molecular weight:

$$\frac{112\,g}{95.22\,g} = 1.18\,\text{mol}$$

Next, we calculate the number of moles of water:

Mass of water = 1.00 L × (1000 cm^{-3} L^{-1}) × (1.00 g cm^{-3}) = 1000 g water

and

$$\text{Moles of water} = \frac{1000\,g}{18.02\,g\,\text{mol}^{-1}} = 55.49\,\text{mol}$$

$$\text{Thus, } x_{MgCl_2} = \frac{1.18\,\text{mol}}{55.49 + 1.18} = 0.021.$$

The mol% of $MgCl_2$ is 2.1%.

Compressibility The fractional change in a fluid's volume per unit change in pressure at constant temperature is the fluid's coefficient of compressibility. Gases, like air are quite compressible. That is, gases have large variations in density (ρ), much larger than in liquids. However any fluid can be compressed in response to the application of pressure (p). For example, water's compressibility at 1 atm is 4.9×10^{-5} atm^{-1}. This compares to the lesser compressibility of mercury (3.9×10^{-6} atm^{-1}) and the much greater compressibility of hydrogen (1.6×10^{-3} atm^{-1}).

A fluid's bulk modulus, E (analogous to the modulus of elasticity in solids) is a function of stress and strain on the fluid (see Fig. 4.9), and is a description of its compressibility. It is defined according to the fluid volume (V):

$$E = \frac{\text{stress}}{\text{strain}} = -\frac{\mathrm{d}p}{\mathrm{d}V/V_1} \tag{4.28}$$

E is expressed in units of pressure (e.g. kPa). Water's $E = 2.2 \times 10^6$ kPa at 20°C.

Surface Tension and Capillarity Surface tension effects occur at liquid surfaces (interfaces of liquid–liquid, liquid–gas, liquid–solid). Surface tension, σ, is the force in the liquid surface normal to a line of unit length drawn in the surface. Surface tension decreases with temperature and depends on the contact fluid. Surface tension is involved in capillary rise and drop. Water has a very high σ value (approximately $0.07\,\mathrm{N\,m^{-2}}$ at 200°C). Of the environmental fluids, only mercury has a higher σ (see Table 4.3).

The high surface tension creates a type of skin on a free surface, which is how an object more dense than water (e.g. a steel needle) can "float" on a still water surface. It is the reason insects can sit comfortably on water surfaces. Surface tension is somewhat dependent on the gas that is contacting the free surface. If not indicated, it is usually safe to assume that the gas is the air in the troposphere.

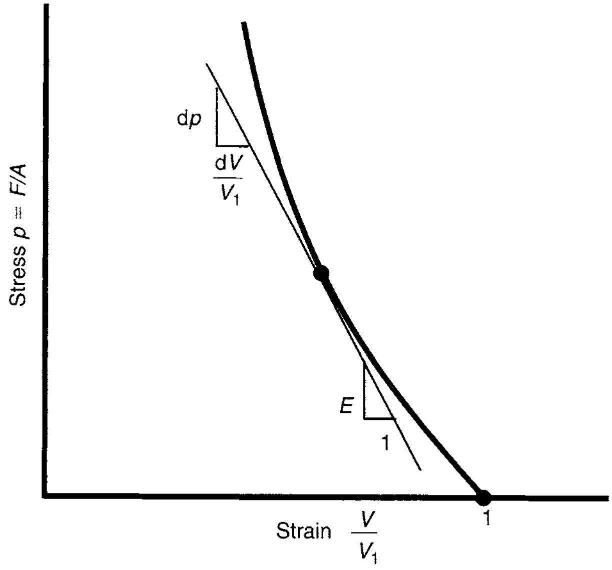

Fig. 4.9. Stress and strain on a fluid, and the bulk modulus of fluids.

TABLE 4.3

Surface Tension (Contact with Air) of Selected Fluids Important to Air Pollution

Fluid	Surface tension, σ (N m^{-1} at 20°C)
Acetone	0.0236
Benzene	0.0289
Ethanol	0.0236
Glycerin	0.0631
Kerosene	0.0260
Mercury	0.519
n-Octane	0.0270
Tetrachloromethane	0.0236
Toluene	0.0285
Water	0.0728

Capillarity is a particularly important fluid property in the design of air pollutant sampling and analytical equipment, such as capillary action in filters and sorption traps used to collect gases and in capillary tubes used in chromatography. Capillarity is also an important factor in physiological response to air pollutants. For example, morphological changes have been observed in lung tissue exposed to ozone. These changes, in part, are due to ozone's effect on the alveolar capillaries and the degradation of capillary endothelia. This leads to less efficient oxygen exchange between the inhaled air and blood, which in turn leads to respiratory and cardiovascular stress.

Capillary rise occurs for two reasons, its adhesion to a surface, plus the cohesion of water molecules to one another. Higher relative surface tension causes a fluid rise to in a tube (or a pore) that is indirectly proportional to the diameter of the tube. In other words, capillarity is greater the smaller the inside diameter of the tube (see Fig. 4.10). The rise is limited by the weight of the fluid in the tube. The rise ($h_{\text{capillary}}$) of the fluid in a capillary is expressed as (Fig. 4.11 displays the variables):

$$h_{\text{capillary}} = \frac{2\sigma\cos\lambda}{\rho_w g R} \tag{4.29}$$

where σ is the fluid surface tension (g s^{-2}), λ is the angle of meniscus (concavity of fluid) in capillary (degrees), ρ_w is the fluid density (g cm^{-3}), g is the gravitational acceleration (cm s^{-1}), and R is the radius of capillary (cm).

The contact angle indicates whether cohesive or adhesive forces are dominant in the capillarity. When λ values are greater than 90°, cohesive forces are dominant; when $\lambda < 90°$, adhesive forces dominate. Thus, λ is dependent on both the type of fluid and the surface to which it comes into contact. For example, water–glass $\lambda = 0°$; ethanol–glass $\lambda = 0°$; glycerin–glass $\lambda = 19°$; kerosene–glass $\lambda = 26°$; water–paraffin $\lambda = 107°$; and mercury–glass $\lambda = 140°$.

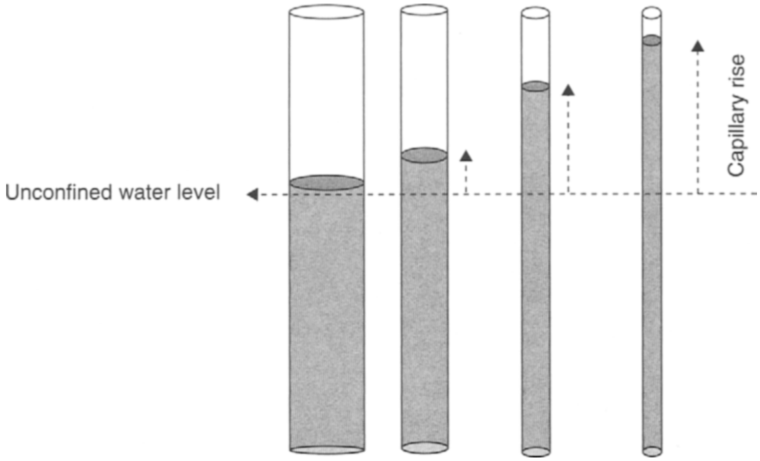

Fig. 4.10. Capillary rise of water with respect to diameter of conduit.

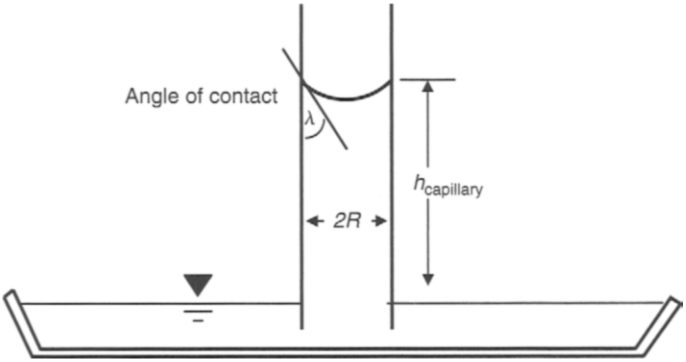

Fig. 4.11. Rise of a fluid in a capillary. In this example, adhesive forces within the fluid are dominant, so the meniscus is concave (i.e. a valley). This is the case for most fluids. However, if cohesive forces dominate, such as the extremely cohesive liquid mercury, the meniscus will be convex (i.e. a hill).

Capillarity Example

What is the rise of contaminated water (i.e. a solution of water and soluble and insoluble contaminants) in a sorption material used to collect gaseous air pollutants that has an average pore space diameter of 0.1 cm, at 18°C and a density of 0.999 g cm^{-3}, under surface tension of 50 g s^{-1} if the angle of contact of the meniscus is 30°?

What would happen if the average pore space were 0.01 cm, with all other variables remaining as stated?

Answer

$$h_{\text{capillary}} = \frac{2\sigma\cos\lambda}{\rho_w g R} = \frac{2\times 80\times\cos 30}{0.999\times 980\times 0.05}\,\text{cm} \cong 0.25\,\text{cm}$$

If the pore space were 0.01 cm in diameter, the rise would be 2.5 cm. However, it is likely that the angle of contact would have also decreased since the angle is influenced by the diameter of the column (approaching zero with decreasing diameter).

Also note that since the solution is not 100% water, the curvature of the meniscus will be different, so the contact angle λ will likely be greater (i.e. less curvature) than the meniscus of water alone. The lower surface tension of the mixture also means that the capillary rise will be less.

Viscosity How much a fluid resists flow when it is acted on by an external force, especially a pressure differential or gravity, is the fluid's viscosity. This a crucial fluid property used in numerous environmental applications, including air pollution plume characterization.

Recall from Bernoulli's equation (4.10) and Fig. 4.6 that if a fluid is flowing in a long, horizontal conduit with constant cross-sectional area, the pressure along the pipe must be constant. But why if we measure the pressure as the fluid moves in the conduit, would there be a *pressure drop*? A pressure difference is needed to push the fluid through the conduit to overcome the drag force exerted by the conduit walls on the layer of fluid that is making contact with the walls. Since the drag force exerted by each successive layer of the fluid on each adjacent layer that is moving at its own velocity, then a pressure difference is needed (see Fig. 4.12). The drag forces are known as *viscous forces*. Thus, the fluid velocity is not constant across the conduit's diameter, owing to the viscous forces. The greatest velocity is at the center (furthest away from the walls), and the lowest velocity is found at the walls. In fact, at the point of contact with walls, the fluid velocity is zero.

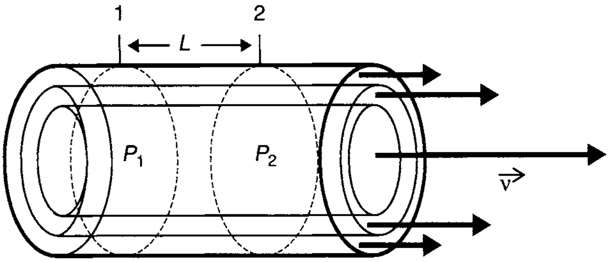

Fig. 4.12. Viscous flow through a horizontal conduit. The highest velocity is at the center of the conduit. As the fluid approaches the wall, the velocity declines and approaches zero.

So, if P_1 is the pressure at point 1, and P_2 is the pressure at point 2, with the two points separated by distance L, the pressure drop (ΔP) is proportional to the flow rate:

$$\Delta P = P_1 - P_2 \tag{4.30}$$

and

$$\Delta P = P_1 - P_2 = I_v R \tag{4.31}$$

where I_v is the volume flow rate, and R is the proportionality constant representing the resistance to the flow. This resistance R depends on the length (L) of pipe section, the pipe's radius, and the fluid's viscosity.

Viscosity Example 1

Workers are being exposed to an air pollutant known to decrease blood pressure in the capillaries, small arteries, and major arteries and veins after the blood is pumped from the aorta. If high-dose studies show an acute drop in the gage pressure of the circulatory system from 100 torr to 0 torr at a volume flow of 0.7 L s^{-1}, give the total resistance of the circulatory system.

Answer

Solving for R from Eq. (4.31), and converting to SI units gives us:

$$\begin{aligned}R &= \Delta P\,(I_v)^{-1}\\ &= (100\,\text{torr})(0.7\,\text{L}\,\text{s}^{-1})^{-1}\,(133.3\,\text{Pa})\,(1\,\text{torr})^{-1}\,(1\,\text{L})\,(10^3\text{cm}^{-3})^{-1}\\ &\quad (1\,\text{cm}^{-3})\,(10^{-6}\text{m}^{-3})\\ &= 1.45\times10^7\,\text{Pa}\,\text{s}\,\text{m}^{-3}\\ &= 1.45\times10^7\,\text{N}\,\text{s}\,\text{m}^{-5}\end{aligned}$$

Two types of viscosity are important in air pollution: absolute viscosity and kinematic viscosity.

Absolute viscosity Physicists define the fluid's coefficient of viscosity by assuming that the fluid is confined between two parallel, rigid plates with equal area. The absolute viscosity of a fluid can be measured by a number of ways, but engineers commonly use the *sliding plate viscometer test*. The test applies two plates separated by the fluid to be measured (see Fig. 4.13).

For Newtonian fluids, the force applied in the viscometer test has been found to be in direct proportion to the velocity of the moving plate and inversely proportional to the length of separation of the two plates:

$$\frac{F}{A} \propto \frac{dv}{dy} \tag{4.32}$$

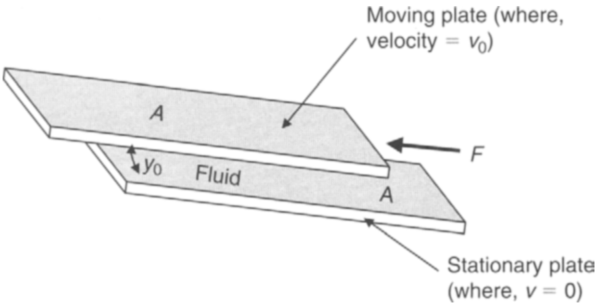

Fig. 4.13. The sliding plate viscometer. A fluid of thickness y_0 is placed between two plates of area A. The top plate moves at the constant velocity v_0 by the exertion of force F. *Source*: Lindeberg, M., *Civil Engineering Reference Manual for the PE Exam*, 8th ed. Professional Publications, Inc., Belmont, CA, 2001.

Using a constant this proportionality can become an equality:

$$\frac{F}{A} = \mu \frac{dv}{dy} \tag{4.33}$$

This equation is known at *Newton's law of viscosity*. Fluids that conform to this law are referred to as Newtonian fluids.[4] The constant, μ, is the fluid's *absolute viscosity*. The μ is also known as the *coefficient of viscosity*, but environmental texts often refer to μ as *dynamic viscosity*. The term *fluidity* is the reciprocal of dynamic velocity.

The inverse relationship between viscosity and fluidity should make sense after some thought. Since the definition of viscosity is the resistance to flow when an external force is applied, then it makes sense that if a substance does a poor job resisting the flow, the substance must have a lot of fluidity. An electrical analogy might be that of conductivity and resistance. If copper wire has much less resistance to electrical flow than does latex rubber, we say that copper must be a good conductor. Likewise, if water at 35°C is less effective at resisting flow downhill (i.e. gravity is applying our force) than is motor oil at the same temperature, we say that the water has less dynamic viscosity than the motor oil. And, we also say that the water has more fluidity than the oil. Before the modern blends of multi-viscosity motor oils, the temperature–viscosity relationship was part of the seasonal rituals of the oil change. Less viscous motor oil (e.g. 10 W) had to used in a car's engine to prepare for the lower temperatures in winter, so that the starter could "turn over" the engine (less viscous oil = less resistance the force of the starter moving the pistons). Conversely, in preparing for summer, a higher viscosity

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[4] See discussion of Newtonian and non-Newtonian fluids earlier in this chapter.

motor oil (commonly 40 W)[5] would be used because the high temperatures in the engine would allow the oil to "blow out" through the piston rings or elsewhere (because the oil was not doing a good job of resisting the force applied by the pistons and shot out of the engine). The newer oil formulations (e.g. 10–40 W) maintain a smaller range of viscosities, so automobile owners worry less about the viscosity.

The $\frac{F}{A}$ term is known as the *shear stress*, τ, of the fluid. The $\frac{\mathrm{d}v}{\mathrm{d}y}$ term is known as the *velocity gradient* or the *rate of shear formation*.[6] So, the shear stress is linear; i.e., it can be expressed as a straight line (in the form $y = mx + b$):

$$\tau = \mu \frac{\mathrm{d}v}{\mathrm{d}y} \tag{4.34}$$

The relationship between the two sides of this equality determines the types of fluids, as shown in Fig. 4.14). Most fluids encountered in environmental studies are Newtonian, including water, all gases, alcohols, and most solvents. Most solutions also behave as Newtonian fluids. Slurries, muds, motor grease and oils, and many polymers behave has *pseudoplastic fluids*; i.e., viscosities decrease with increasing velocity gradient. They are easily pumped, since higher pumping rates lead to a less viscous fluid. Some slurries behave as *Bingham fluids* (e.g. behave like toothpaste or bread dough), where the shear formation is resisted up to a point. For example, depending on their chemical composition, slurries used in wet scrubbers to collect gases (e.g. sulfur dioxide), may behave as Bingham fluids. The rare *dilatant fluids* are sometimes encountered in environmental engineering applications, such as clay slurries used as landfill liners and when starches and certain paints and coatings are spilled. These can be difficult fluids to remove and clean up, since their viscosities increase with increasing velocity gradient, so pumping these fluids at higher rates can lead to their becoming almost solid with a sufficiently high shear rate. *Plastic fluids* (see Fig. 4.15) require the application of a finite force before any fluid movement.

Categorizing and characterizing fluids according to their behavior under shear stress and velocity gradient is not absolute. For example, a Bingham fluid can resist shear stresses indefinitely so long as they are small, but these fluids will become pseudoplastic at higher stresses. Even if all conditions remain constant, viscosity can also change with time. A *rheopectic fluid* is one where viscosity increases with time, and a *thixotropic fluid* is one that has decreasing viscosity with time. Those fluids that do not change with time are referred to as *time-independent fluids*. Colloidal materials, like certain components of sludges, sediments, and soils, act like thixotropic fluids. That is, they

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[5] In the 1960s, many of us went further. We used 50 W or even higher viscosity racing formulas even if we never really allowed our cars to ever reach racing temperatures! We often applied the same logic for slicks, glass packs, four-barrel carburetors, and other racing equipment that was really never needed, but looked and sounded awesome!

[6] The $\mathrm{d}v\,\mathrm{d}y^{-1}$ term is also known as the *rate of strain* and the *shear rate*.

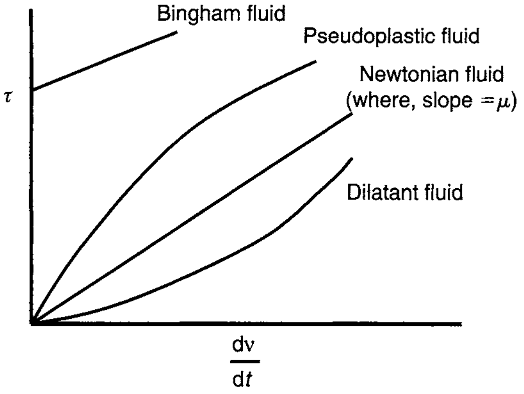

Fig. 4.14. Hypothetical fluid types according to shear stress (τ) behavior relative to velocity gradient. *Source*: Lindeberg, M., *Civil Engineering Reference Manual for the PE Exam,* 8th ed. Professional Publications, Inc., Belmont, CA, 2001.

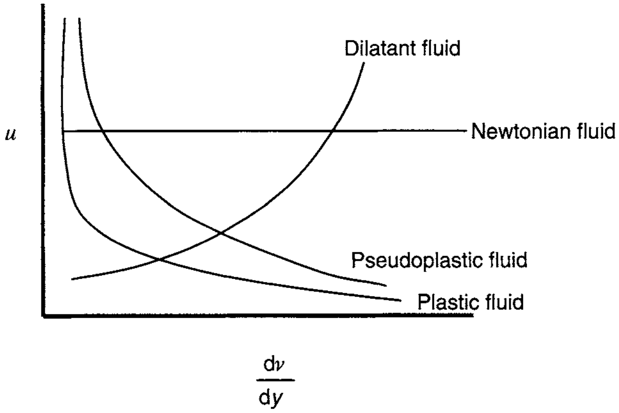

Fig. 4.15. Hypothetical fluid types according to viscosity (μ) and shear rate (velocity). *Source*: Lindeberg, M., *Civil Engineering Reference Manual for the PE Exam,* 8th ed. Professional Publications, Inc., Belmont, CA, 2001.

experience a decrease in viscosity when the shear is increased. However, there is no *hysteresis,* meaning that the viscosity does not return to the original state with the ceasing of the agitation.

There is a seeming paradox between viscosity and temperature. As a general rule, temperature is inversely proportional to viscosity of liquids, but temperature is directly proportional to the viscosity of gases. Viscosity of liquids is predominantly caused by molecular cohesion. These cohesive forces decrease with increasing temperature, which is why viscosity decreases with increasing temperature. Gas viscosity is mainly kinetic molecular in its origin, so increasing temperature means that more collisions will occur between

TABLE 4.4

Absolute Viscosity of Fluids Important to Health and Environmental Studies. ***Source*: Tipler, P., *Physics for Scientists and Engineers*, Vol. 1. W.H. Freeman and Co., New York, 1999.**

Fluid	Temperature (°C)	Absolute viscosity, μ (Pa s)
Water	0	1.8×10^{-3}
	20	1×10^{-3}
	60	6.5×10^{-2}
Whole human blood	37	4×10^{-3}
SAE 10 motor oil	30	2×10^{-1}
Glycerin	0	10
	20	1.4
	60	8.1×10^{-2}
Air	20	1.8×10^{-5}

molecules. The more the gas is agitated, the greater the viscosity, so gas velocity increases with increasing temperatures.

The viscosity of liquids increases only slightly with increasing pressure. Under environmental conditions, absolute viscosity can be considered to be independent of pressure.

Absolute viscosity units are mass per length per time (e.g. $\mathrm{g\,cm^{-1}s^{-1}}$). The coefficients for some common fluids are provided in Table 4.4. Note the importance of temperature in a substance's absolute viscosity, e.g. the several orders of magnitude decrease with only a 20°C increase in glycerin.

Viscosity Example 2

A liquid with the absolute viscosity of $3 \times 10^{-5}\,\mathrm{g\,s\,cm^{-1}}$ flows through rectangular tube in an air sampling device. The velocity gradient is $0.5\,\mathrm{m\,s^{-1}cm^{-1}}$. What is the shear stress in the fluid at this velocity gradient?

Answer

$$
\begin{aligned}
\tau &= \mu \frac{dv}{dy} \\
&= (3 \times 10^{-5}\,\mathrm{g\,s\,cm^{-1}})(0.5\,\mathrm{m\,s^{-1}\,cm^{-1}})(100\,\mathrm{cm\,m^{-1}}) \\
&= 1.5 \times 10^{-3}\,\mathrm{g\,cm^{-2}}
\end{aligned}
$$

Kinematic viscosity The ratio of absolute viscosity to mass density is known as *kinematic viscosity* (ν):

$$\nu = \mu \rho^{-1} \tag{4.35}$$

The units of ν are area per second (e.g. cm^{2}s^{-1} = stoke). Because kinematic viscosity is inversely proportional to a fluid's density, ν is highly dependent on temperature and pressure. Recall that absolute viscosity is only slightly affected by pressure. Table 4.5 can be used to convert most of the units of μ and ν.

Laminar versus Turbulent Flow: The Reynolds Number At a sufficiently high velocity, a fluid's flow ceases to be laminar and becomes turbulent. A dimensionless Reynolds number (N_R) is used to differentiate types of flow. The N_R is expressed as the ratio of inertial to viscous forces in a fluid:

$$N_R = \frac{\text{Inertial forces}}{\text{Viscous forces}} \tag{4.36}$$

TABLE 4.5

Viscosity Units and Conversions

Multiply:	By:	To obtain:
Absolute viscosity (μ)		
centipoise (cP)	1.0197×10^{-4}	kg f s m^{-2}
cP	2.0885×10^{-5}	lb f-s ft^{-2}
cP	1×10^{-3}	Pa s
Pa s	2.0885×10^{-3}	lb f-s ft^{-2}
Pa s	1000	cP
dyne s cm^{-2}	0.10	Pa s
lbf-s ft^{-2}	478.8	poise (P)
slug ft^{-1}s^{-1}	47.88	Pa s
Kinematic viscosity (ν)		
ft^{2}s^{-1}	9.2903×10^{4}	centistoke (cSt)
ft^{2}s^{-1}	9.2903×10^{-2}	m^{2}s^{-1}
m^{2}s^{-1}	10.7639	ft^{2}s^{-1}
m^{2}s^{-1}	1×10^{6}	cSt
cSt	1×10^{-6}	m^{2}s^{-1}
cSt	1.0764×10^{-5}	ft^{2}s^{-1}
μ to ν		
cP	$1/\rho$ (g cm^{-3})	cSt
cP	$6.7195 \times 10^{-4}/\rho$ in lbm ft^{-3}	cSt
lbf-s ft^{-2}	$32.174/\rho$ in lbm ft^{-3}	ft^{2}s^{-1}
kgf s m^{-2}	$9.807/\rho$ in kg m^{-3}	m^{2}s^{-1}
Pa s	$1000/\rho$ in g cm^{-3}	cSt
ν to μ		
cSt	ρ in g cm^{-3}	cP
cSt	1.6×10^{-5}	Pa s
m^{2}s^{-1}	$0.10197 \times \rho$ in kg m^{-3}	kg f s m^{-2}
m^{2}s^{-1}	$1000 \times \rho$ in g cm^{-3}	Pa s
ft^{2}s^{-1}	$3.1081 \times 10^{-2} \times \rho$ in lb m ft^{-3}	lb f-s ft^{-2}
ft^{2}s^{-1}	$1.4882 \times 10^{3} \times \rho$ in lb m ft^{-3}	cP

The inertial forces are proportional to the velocity and density of the fluid, as well as to the diameter of the conduit in which the fluid is moving. An increase in any of these factors will lead to a proportional increase in the momentum of the flowing fluid. We know from our previous discussion that the coefficient of viscosity or absolute viscosity (μ) represents the total viscous force of the fluid, so, N_R can be calculated as:

$$N_R = \frac{D_e v \rho}{\mu} \tag{4.37}$$

where D_e is the conduit's equivalent diameter, which is a so-called "characteristic dimension"[7] which evaluates the fluid flow as a physical length.

It is actually the inside diameter (i.d.) of the conduit, vent, or pipe. Recall that $\mu \rho^{-1}$ is the kinematic viscosity v, so the Reynolds number can be stated as the relationship between the size of the conduit, the average fluid velocity ν, and v:

$$N_R = \frac{D_e \nu}{v} \tag{4.38}$$

When fluids move at very low velocities, the bulk material moves in discrete layers parallel to one another. The only movement across the fluid layers is molecular motion, which creates viscosity. Such a flow is *laminar* (see Fig. 4.16). Laminar flow is more common in water than in air, especially in low velocity systems like ground water.

With increasing fluid velocity, the bulk movement changes, forming eddy currents that create three-dimensional mixing across the flow stream. This is known as *turbulent* flow. Most pollution control equipment and atmospheric plumes are subjected to turbulent flow (see Fig. 4.17).

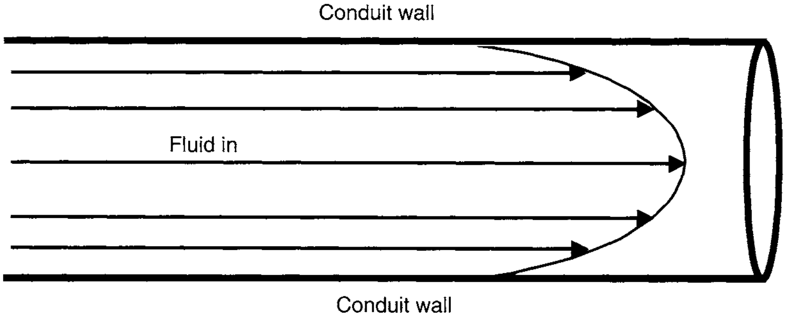

Fig. 4.16. Laminar flow in closed conduit.

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[7] Other equivalent diameters for fully flowing conduits are the annulus, square, and rectangle. Equivalent diameters for partial flows in conduits are the half-filled circle, rectangle, wide and shallow stream, and trapezoid. For calculations of these diameters, see Lindeberg, M., *Civil Engineering Reference Manual for the PE Exam*, 8th ed. Professional Publications, Inc., Belmont, CA, 2001.

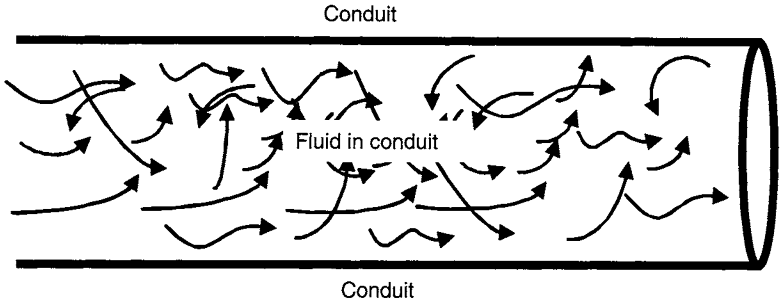

Fig. 4.17. Turbulent flow in a closed conduit.

Flows in closed conduits with Reynolds numbers under 2100 are usually laminar.[8] Due to the relatively low velocities associated with this type of flow, they are mainly encountered with liquids such as water moving through underground strata and blood flowing in arteries. In open atmospheric conditions, such as a plume of an air pollutant, laminar flow is quite rare. Flows with Reynolds numbers greater than 4000 are usually turbulent. The range of N_R values between these thresholds are considered "critical flows" or "transitional flows," that show properties of both laminar and turbulent flow in the flow streams. Usually, if the flow is in the transition region, engineers will design equipment as if the flow were turbulent, as this is the most conservative design assumption.

Under laminar conditions, the fluid particles adhere to the conduit wall. The closer to the wall that a particle gets, the more likely it will adhere to the wall. Laminar flow is, therefore, parabolic and its velocity at the conduit wall is zero (see Fig. 4.16). Laminar flow velocity is greatest at the pipe's center ($v_{\max}$ in the Fig. 4.18), and is twice the value of the average velocity, v_{average}:

$$v_{\text{average}} = \frac{\dot{V}}{A} = \frac{v_{\max}}{2} \text{(laminar)} \tag{4.39}$$

where $\dot{V}$ is the volumetric fluid velocity and A is the cross-sectional area of the pipe.

Turbulent flow velocity, on the other hand, has no relationship with the proximity to the wall due to the mixing (see Fig. 4.17). So, all fluid particles in a turbulent system are assumed to share the same velocity (as depicted in Fig. 4.18), known as the average velocity or bulk velocity:

$$v_{\text{average}} = \frac{\dot{V}}{A} \tag{4.40}$$

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[8] The literature is not consistent on the exact Reynolds numbers as thresholds for laminar versus turbulent flow. Another value used by engineers is 2300.

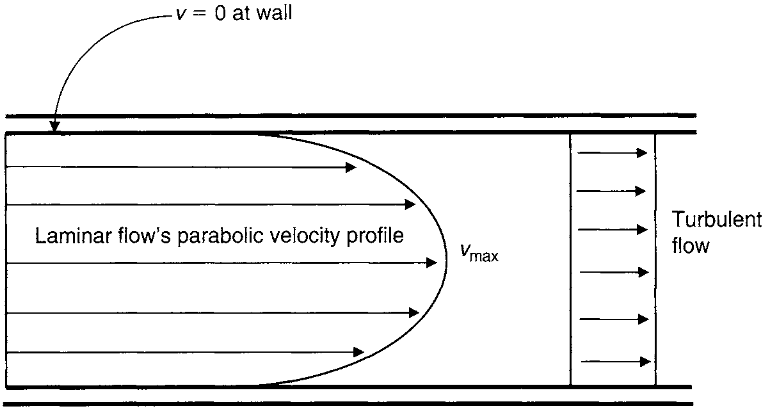

Fig. 4.18. Velocity distributions of laminar and turbulent flows.

There is a thin layer of turbulent flow near the wall of the conduit where the velocity increases from zero to v_{average}, known as the *boundary layer*. In fact, no flow is entirely turbulent and there is some difference between the centerline velocity and v_{average}. However, for many environmental applications the assumption of consistently mixed flow is acceptable.

Reynolds Number Example 1

Find the Reynold's number of water flowing in a 0.2 i.d. m pipe at $0.1\,\text{m}\,\text{s}^{-1}$. Assume that the water's coefficient of viscosity is $8 \times 10^{-3}\,\text{N}\,\text{s}\,\text{m}^{-3}$ and density is $1000\,\text{kg}\,\text{m}^{-3}$.

Solution

Use Eq. (4.38).

$$
\begin{aligned}
N_R &= \frac{D_e v \rho}{\mu} \\
&= \frac{(1000\,\text{kg}\,\text{m}^3)(0.1\,\text{m}\,\text{s}^{-1})(0.2\,\text{m})}{8 \times 10^{-3}\,\text{N}\,\text{s}\,\text{m}^{-2}} \\
&= 2500
\end{aligned}
$$

Reynolds Number Example 2

How is this flow characterized? Assuming this flow is representative of a cooling tower in a power plant, what kind of flow should be assumed in selecting pumps and other equipment?

Solution

Since the N_R is greater than 2100, but less than 4000, the flow is considered transitional or critical. Therefore, the conservative design calls for an assumption that the flow is turbulent.

The fundamental fluid properties and physical principles discussed in this chapter are important in all environmental sciences. In Chapter 5, we will extend these and other physical concepts specifically to the atmosphere.

QUESTIONS

1. Give an example in air pollution of a clearly physical phenomenon, an example of a clearly chemical phenomenon, and an example of a phenomenon that has qualities of both, that is a physicochemical phenomenon.
2. How does the Bernoulli effect play a role in air pollution engineering?
3. Why is density important in environmental measurements?
4. Why is an understanding of capillarity important to air pollution? Give three possible reasons.
5. Give a scenario where viscosity of a fluid needs to be understood to protect air quality. What is the importance of the Reynolds number in your scenario?