# 1

# FUNDAMENTALS

In this chapter we consider the fundamentals concerning fluid flow systems, such as the systems of units employed in this work, the physical properties of fluids, and the nature of fluid flow.

## 1.1 SYSTEMS OF UNITS

This book employs two systems of units: the U.S. Customary System (or USCS) and the International System (or SI, for Système International). The latter is based on the metric system, a system devised in France during the French Revolution in the late 1700s, but uses internationally standardized physical constants. Conversions between the systems may be found in Appendix C.

The USCS is virtually indistinguishable from the English gravitational system. There is some confusion in regard to the differences. Some authors imply that in USCS the slug is basic and the pound is derived, while others hold that the pound is basic and the slug is derived. In the English gravitational system the latter is assumed. For general engineering use it does not matter which is basic, because both systems agree that there is the slug for mass, the pound for force, the foot for length, and the second for time. This is all that need concern us in this work. The SI, derived from the metric system and having a much shorter pedigree, is consequently much more standardized.

Much confusion has resulted from the use in both English and metric systems of the same terms for the units of force and mass. To help eliminate the ambiguity owing to this double use the following treatment has been adopted.

The equation relating force, mass, and acceleration is

$$F = ma, \tag{1.1}$$

where $F$, $m$, and $a$ are defined in the nomenclature. In SI the unit of mass, the kilogram, is basic. The unit of force is derived by means of the equation above and is given a unique name, the newton. Mass is never referred to by force units and vice versa. In the English gravitational system (which predates the USCS) and the USCS, a similar set of units is available and familiar to engineers, but it is not uniformly used. The unit of force, the pound, can be considered to be basic and the unit of mass derived by means of the relation above. It is often called the slug. While the slug is not often used, its insertion here need not pose any inconvenience. Where mass units are called for they may be easily obtained from the pound-force unit by the use of Equation 1.1. By use of these conventions any fundamental equation given in this book may be used with either SI or English units.

It should be noted that Equation 1.1 returns, in the English gravitational system, a mass with units of $\mathrm{lb_f\text{-}s^2/ft}$. This is not easily recognizable, so the engineering community has somewhat arbitrarily chosen the term “slug” to name the mass instead of $\mathrm{lb_f\text{-}s^2/ft}$. Similarly, in SI, the force that comes out of the equation has units of $\mathrm{kg\text{-}m/s^2}$, and this force has been given the name “newton.” The equation does not contain a factor that transforms $\mathrm{lb_f\text{-}s^2/ft}$ to “slugs” or $\mathrm{kg\text{-}m/s^2}$ to “newtons.”

---

*Pipe Flow: A Practical and Comprehensive Guide*, First Edition. Donald C. Rennels and Hobart M. Hudson.

We knowingly or unknowingly assume that there is an implicit conversion factor that changes the names of these units. This factor for SI is N/(kg-m/s$^2$)/(kg), and in the English gravitational system it is lb$_f$/slug-ft/s$^2$. If you call these conversion factors "$C_g$," Equation 1.1 becomes:

$$F \text{ newtons} = [C_g, \text{N/(kg-m/s}^2)][m \text{ kg}] \times [a(\text{m/s}^2)],$$

or

$$F \text{ lb}_\text{f} = [C_g, \text{lb/(slug-ft/s}^2)][m \cdot \text{slug}] \times [a(\text{ft/s}^2)].$$

The numeric value of the conversion factor is 1.000, so it does not change the number obtained, but only the name of the number. This may be the reason many writers subscript the $g$ with a $c$ to obtain $g_c$, when $a$ is the acceleration of gravity.

Unfortunately the modern engineer must deal with mixed units and nomenclature used in some current practice and remaining from past practice. Conversions are offered in Appendix C that can help the user to work with mixed units. (Some secondary equations are given in which the units are mixed for the convenience of users of the English gravitational system. These equations and the units they require will be clearly indicated in the text.) Appendix C gives the important base units and derived units used here as well as the most frequently used conversions between systems.

## 1.2 FLUID PROPERTIES

Understanding the subject of pressure loss in fluid flow requires an understanding of the fluid properties that cause it. The principal concepts of interest in pressure loss due to flow are pressure, density, velocity, energy, and viscosity. Of secondary interest are temperature and heat.

### 1.2.1 Pressure

*Pressure*: The force per unit area exerted by a fluid on an arbitrarily defined boundary or surface, usually the walls of the conduit in which the fluid is flowing, or its cross section. Pressures are measured and quoted in different ways. A picture of pressure relationships can be gained from a diagram such as that of Figure 1.1, in which are shown two typical pressures, one above, and the other below, atmospheric pressure.*

*Absolute Pressure:* The pressure measured with respect to a datum of absolute zero pressure in which there are no fluid forces imposed on the boundary.[†]

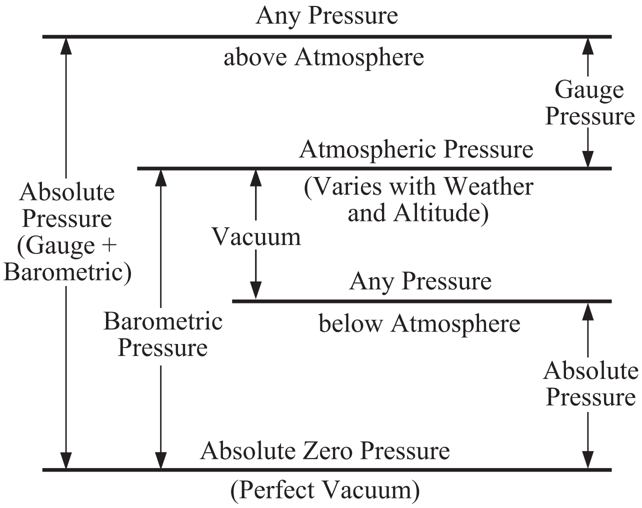

**FIGURE 1.1.** Pressure relationships.

*Atmospheric Pressure*: The absolute pressure of the local atmosphere.

*Standard Atmospheric Pressure*: The absolute pressure of the standard atmosphere at mean sea level. Standard atmospheric pressure, or one atmosphere, is 14.696 lb/in$^2$, 760.0 mm of mercury, $1.01325 \times 10^5$ N/m$^2$ (pascals), or 1.01325 bar.

*Barometric Pressure*: A barometer is an instrument used to measure atmospheric pressure by using water, air, or mercury. Thus atmospheric pressure is often called barometric pressure.

*Critical Pressure*: The pressure of a pure substance at its *critical state*; where the density of the saturated liquid is the same as the density of the saturated vapor. At pressures higher than the critical, a liquid may be heated from a low temperature to a very high one without any discontinuity indicating a change from the liquid to vapor phase. Values of critical pressure for selected gases are given in Appendix D.3.

*Differential Pressure*: The calculated or measured difference in pressure between any two points of interest.[‡]

*Gauge Pressure*: The pressure measured with respect to local atmospheric pressure. This is the pressure read by the common pressure gauge whose detecting element is a coil of flattened tube. (Sometimes this pressure is relative to standard atmospheric pressure. The reader is advised to determine which datum is used in other works or information sources.)[§]

---

[*] In the English system of units, pressure $p$ is expressed in pounds per square inch, or psi.

[†] Absolute pressure is often expressed as psia in the English system.

[‡] Differential pressure is often expressed as psid in the English system.

[§] Gauge pressure is often expressed as psig in the English system.

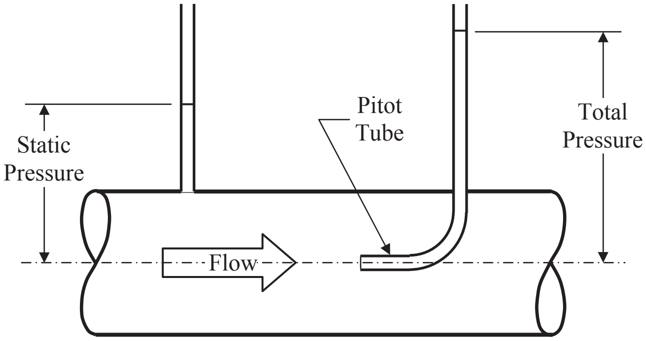

**FIGURE 1.2.** Total and static pressure.

*Total Pressure*: The pressure resulting from a moving fluid being brought to rest isentropically (without loss), as, for example, against a blunt object. (The kinetic energy of motion is converted to pressure when the fluid is brought to rest.) Total pressure is also known as stagnation pressure and pitot pressure (see Fig. 1.2).

*Static Pressure*: The pressure in a moving fluid before it is brought to rest. A pipe wall tap samples static pressure (see Fig. 1.2).

*Vacuum*: A pressure below local atmospheric pressure; often expressed as a negative pressure with respect to standard atmospheric pressure.

*Vapor Pressure*: The absolute pressure of a pure vapor in equilibrium with its liquid phase.

### 1.2.2 Density

*Mass Density*: The amount of material contained in a unit volume, measured in terms of its mass.

*Weight Density*: The amount of material contained in a unit volume, measured in terms of the force (weight) standard gravity exerts on the contained mass.

*Specific Volume*: The volume occupied by a unit mass or weight of material. (Which means it must be inferred from the units used. In the English system they will be $ft^3$/lb[force]; in SI they will be $m^3$/kg[mass].)

### 1.2.3 Velocity

*Velocity*: The speed of motion of a fluid with respect to a uniform datum. In pressure drop considerations it is usually used loosely with no direction implied. However, in impulse-momentum considerations, direction is an essential part of the measurement.

*Average Velocity*: A derived speed of a moving fluid whose various regions are not moving at the same speed but which accounts for the mass flux over the cross section of interest through which the fluid is moving.

*Local Velocity*: The actual speed of a moving fluid at a particular point of interest.

### 1.2.4 Energy

*Energy (Work Energy)*: A measure of the ability of a substance to do or absorb work. It is usually measured in foot-pounds or newton-meters. (Newton-meters is also known as joules in SI.) Energy may exist in five forms: (1) potential, owing to a substance's elevation above an arbitrary datum; (2) pressure, which is a measure of a fluid's ability to lift some of itself to a level above an arbitrary datum or propel some of itself to a velocity; (3) kinetic, which resides in a substance's speed or velocity; (4) heat, which ultimately is a measure of the kinetic energy of the molecules of a substance; and (5) work. Work, in the case of fluid flow, is actually an effect of pressure moving some resistance. The work may be added to or subtracted from a fluid to change the status of the other four forms of energy. Pressure energy is sometimes called flow work because of its role in transferring work from one end of a conduit to another. Heat is considered separately below.

### 1.2.5 Viscosity

*Viscosity*: The resistance offered by a fluid to relative motion, or shearing, between its parts.

*Absolute Viscosity*: The frictional or shearing force per unit area of relatively moving surfaces per unit velocity for a unit separation of the surfaces. It is also called coefficient of viscosity and dynamic viscosity.

*Kinematic Viscosity*: Absolute viscosity per unit mass per unit volume of the flowing fluid. (A fluid's kinematic viscosity is its absolute viscosity divided by its mass density.)

### 1.2.6 Temperature

*Temperature*: In most fluid flow problems, temperature will refer simply to warmth (or lack of it), such as is perceived by our sense of touch and will be used to establish other fluid properties such as density and viscosity. It is usually measured on a somewhat arbitrary scale. The English system commonly uses the Fahrenheit scale, devised by the fifteenth-century German physicist Gabriel Fahrenheit [1]. It is based on the lowest temperature he could attain with a salt and ice mixture (assigned a value of 0°F) and human body temperature (to which he tried to assign a value of 96°F). This did not work out well and he ended up assigning 32°F to the melting point of ice and 212°F to the boiling point of water. The SI temperature scale (the Kelvin scale) is an absolute scale using the centigrade degree. The centigrade scale was devised by Swedish astronomer Anders Celsius in 1742 and incorporated into the metric system adopted in France at the close of the French Revolution [1]. On this scale—officially called Celsius since 1948—the melting point and boiling point of water at standard atmospheric pressure were assigned values of 0 and 100°C respectively.

*Absolute Temperature*: Temperature measured from absolute zero. It was noted in the late 1700s by the French physicist Jacques Charles (1746–1823) that gases expand and contract in direct proportion to their temperature changes. On a suitably chosen scale their volumes are thus directly proportional to their temperatures. The extrapolated temperature of zero volume according to the kinetic theory of gases is also the point at which molecular activity—and hence heat content—vanishes. No lower temperature is possible and so this temperature is called absolute zero. Two temperature scales based on this zero point are in common use. One, utilizing the Fahrenheit degree, is called the Rankine scale; temperatures on this scale are marked °R. The other, utilizing the Celsius degree, is called the Kelvin scale and its temperatures are marked K. The temperature 0°F corresponds to 459.67°R, and 0°C is identical to 273.15 K. Absolute zero is thus –459.67°F or –273.15°C.

*Critical Temperature:* The temperature of a pure substance at its *critical state*, above which its gas phase cannot be liquefied by the application of pressure, because at the critical temperature the latent heat of vaporization vanishes and the liquid cannot be distinguished from the gas. Values of critical temperature for selected gases are given in Appendix D.3.

### 1.2.7 Heat

*Heat (Heat Energy)*: Heat is the measure of thermal energy contained in a substance. In fluid flow problems generally only sensible heat (i.e., heat obvious to the sense of touch or yielding a change in temperature) is of interest. It can be measured in the same units as work energy and indeed is interchangeable with energy. Usually heat is measured in units related to the heat–temperature relationship of water. In the English system the unit is the British thermal unit (usually abbreviated Btu). In SI it is the joule. The conversion to mechanical energy is the mechanical equivalent of heat. Its value is given in Appendix C.1.

*Specific Heat*: The measure of the change of heat capacity of a unit weight or mass of a substance for a unit change of temperature. It is almost always expressed in heat units, that is, Btu or joule. The units of specific heat are thus Btu/lb-R (or Btu/lb-F) and J/kg-K (or J/kg-C).

## 1.3 IMPORTANT DIMENSIONLESS RATIOS

Researchers have devised many dimensionless ratios in order to describe the behavior of physical processes. The most important to us in analyzing pressure drop in fluid systems are described in the succeeding sections.

### 1.3.1 Reynolds Number

Named for the British engineer Osborne Reynolds (1842–1912), the Reynolds number is the ratio of momentum forces to viscous forces. It is extremely important in quantifying pressure drop in fluids flowing in closed conduits. It is given by:

$$N_{\mathrm{Re}} = \frac{VD\rho_w}{\mu g} = \frac{\dot{w}D}{\mu g A} \quad \text{(English)}, \tag{1.2a}$$

$$N_{\mathrm{Re}} = \frac{VD\rho_m}{\mu} = \frac{\dot{m}D}{\mu A} \quad \text{(SI)}. \tag{1.2b}$$

### 1.3.2 Relative Roughness

This quantity, as with the Reynolds number above, is extremely important in finding pressure drop in fluids flowing in pipes. It is rarely, if ever, assigned a symbol; but for illustration here let it be called $R_{\mathrm{R}}$. It is defined as:

$$R_{\mathrm{R}} = \frac{\varepsilon}{D},$$

where $\varepsilon$ is the absolute roughness of the pipe inner wall and $D$ is the pipe inside diameter. (In practice it is usually just called $\varepsilon/D$.)

### 1.3.3 Loss Coefficient

The loss coefficient, or resistance coefficient, is the measure of pressure drop in fluid systems. It is defined as:

$$K = f\frac{L}{D}, \tag{1.3}$$

where:

$K$ = loss coefficient measured in *velocity heads*,

$f$ = Darcy friction factor,

$L$ = length of pipe stretch for which the resistance coefficient applies, and

$D$ = inside diameter of the pipe stretch.

More will be said about $f$ and $K$ in Chapters 3 and 8.

### 1.3.4 Mach Number

Named for the Czech physicist Ernst Mach (1838–1916), the Mach number is the ratio of the local fluid velocity $u$ to the acoustic velocity A. It is very useful in describing compressible flow phenomena. It is given by:

$$M = \frac{u}{\mathrm{A}}. \tag{1.4a}$$

The average velocity $V$ is usually substituted when the flow is in a conduit and the velocity profile is fairly flat. With this convention, the equation becomes:

$$M = \frac{V}{\mathrm{A}}. \tag{1.4b}$$

### 1.3.5 Froude Number

The *Froude number* $N_{\mathrm{Fr}}$ specifies the ratio of inertia force to gravity force on an element of fluid. It is named for William Froude, an English engineer and naval architect (1810–1879), who, in the later half of the nineteenth century, pioneered in the investigation of ship resistance by use of models. The Froude number is used in the investigation of similarity between ships and models of them. In this role, it is defined as the ratio of the velocity of a surface wave and the flow velocity. Our interest is in its application to pipe flow where the pipe is not flowing full. In this context it is expressed as:

$$N_F = \frac{V}{\sqrt{gD}} = \frac{V}{\sqrt{2gR}}, \tag{1.5}$$

where $V$ is the characteristic velocity, $g$ is the acceleration of gravity, $D$ is the pipe diameter, and $R$ is the pipe radius. The Froude number, unlike the Reynolds number, is independent of viscosity and so it applies to inviscid flow analysis.

### 1.3.6 Reduced Pressure

Reduced pressure, along with reduced temperature (described below), is useful in quantifying departures from the ideal state in gases. Reduced pressure is given by:

$$P_r = \frac{P}{P_c},$$

where $P$ is the pressure of interest and $P_c$ is critical pressure.

### 1.3.7 Reduced Temperature

As with reduced pressure described above, reduced temperature helps to reduce the state point of most gases to a common base, making it possible to quantify departures of most gases from the ideal equation describing the relationship between pressure, temperature, volume, and quantity of substance (the equation of state, described below). Reduced temperature is given by:

$$T_r = \frac{T}{T_c},$$

where $T$ is the temperature of interest and $T_c$ is critical temperature.

## 1.4 EQUATIONS OF STATE

This section presents various equations which describe the physical properties of fluids—principally the fluid's density as a function of pressure and temperature.

### 1.4.1 Equation of State of Liquids

An "equation of state of liquids" is not commonly expressed. This is because in usual engineering fluid-flow problems, the volume properties of the liquid are scarcely affected by changes in temperature or pressure in the flow path. Where their properties are significantly affected it is customary (because it is easiest and sufficiently accurate) to break the problem into small enough segments wherein the properties may be considered to be constant. Where this approach is not satisfactory, as, for instance, when dealing with liquids at pressures above the critical pressure, equations of state of liquids are available in the literature. Attention is directed to the works by Reid et al. [2] and Poling et al. [3], produced a quarter-century apart, which reflect the growth in information available in the literature on this subject.

### 1.4.2 Equation of State of Gases

Because gases exhibit large changes in volume, pressure, or temperature for comparable changes in one or both of the remaining of these three important variables, it has been necessary to formulate a workable expression relating them. The expression is called the equation of state. Two-variable relationships were discovered by Robert Boyle (1627–1691) and by Jacques Charles (1746–1823) and Joseph Gay-Lussac (1778–1850), which were soon combined into the perfect gas law:

$$PV = mRT, \tag{1.6a}$$

where $m$ = mass of the gas, V is the volume, and $R$ is the individual gas constant; or

$$PV = n\bar{R}T, \tag{1.6b}$$

where $n$ = number of mols of gas considered and $\bar{R}$ is the universal gas constant. (In the English system Eq. 1.6a is usually written $PV = wRT$, where $w$ = weight, lb, and the $R$ used is expressed in weight units.)

Equation 1.6 adequately describes real gas behavior when pressure is low with respect to the critical pressure and temperature is high with respect to the critical temperature. However, with increasing pressure or decreasing temperature, or both, this relation departs increasingly from real gas behavior. A coefficient can be added to account for the departure, called the *compressibility factor*:

$$PV = zmRT, \tag{1.7}$$

where $z$ is a function of the temperature and pressure of the gas. Dutch physicist Johannes van der Waals (1837–1923) noted that when $z$ is plotted versus reduced pressure, that is, actual pressure divided by the critical pressure, for constant reduced temperature, that is, actual temperature divided by the critical temperature, the plotted points for any given reduced temperature for most gases fall into a narrow band [4]. If a line is faired through each band for each reduced temperature, a chart called a *compressibility chart* is obtained. A plot of this kind was published by L. C. Nelson and E. F. Obert in 1954 [5]. An example is shown in Figure 1.3 [3].* Many attempts have been made to find an analytic function, an equation of state, to describe this behavior, with varying success. Most of these "real gas" equations of state are limited in range of applicability. Two particularly attractive equations (solutions for $z$), suitable for wide ranges of pressure and temperature, the Redlich–Kwong equation and the Lee–Kesler equation, are described in Appendix D. Scores more are described by Poling et al. [3]. The utility of these equations is illustrated in Chapter 4, "Compressible Flow."

## 1.5 FLUID VELOCITY

As stated in Section 1.2, velocity (so called; more accurately it would be called speed) is usually considered to be uniform over the cross section of flow. In reality, it is not. The fluid in contact with the conduit wall must be at zero velocity, and velocity ordinarily increases toward the center. The assumption of uniform velocity immensely simplifies fluid flow calculations. There is an inaccuracy introduced by this assumption, but, fortunately, it usually does not affect the confidence level of fluid flow computations. The inaccuracies can be quantified and will be considered in the following chapter.

Another assumption that is usually made is that the velocity is one-dimensional, that is, that radial components of flow velocities are inconsequential. Inaccuracies introduced by this assumption are small and are absorbed by the loss coefficients.

## 1.6 FLOW REGIMES

In the study of fluid flow it has long been recognized that there are two distinct kinds of flow or flow regimes. The first is characterized by preservation of layers or laminae in the flow stream. This kind of flow is called *laminar* or *streamline* flow. In cylindrical conduits the layers are cylindrical, the local velocities are strictly parallel to the conduit axis, and they vary parabolically in velocity from zero at the wall to a maximum at the center. The second is characterized by destruction and mixing of the layers seen in laminar flow, and the local motions in the fluid are chaotic or turbulent. This kind of flow is thus appropriately called *turbulent* flow. In circular conduits the axial velocity distribution is more nearly uniform than it is in laminar flow, although local velocity at the pipe wall is still zero. Laminar and turbulent flow velocity profiles are illustrated in Figure 1.4. Because their effects will be treated in the following chapter you need to know that these two types of flow exist.

---

* Large charts of the compressibility factor are available. One is reprinted by Poling et al [3]. Where more precision is desired, a computer program, called *MIPROPS*, which calculates many fluid properties, including density, viscosity, entropy, and acoustic velocity, was published by the National Bureau of Standards (now the National Institute of Standards and Technology) and is available from the Department of Commerce.

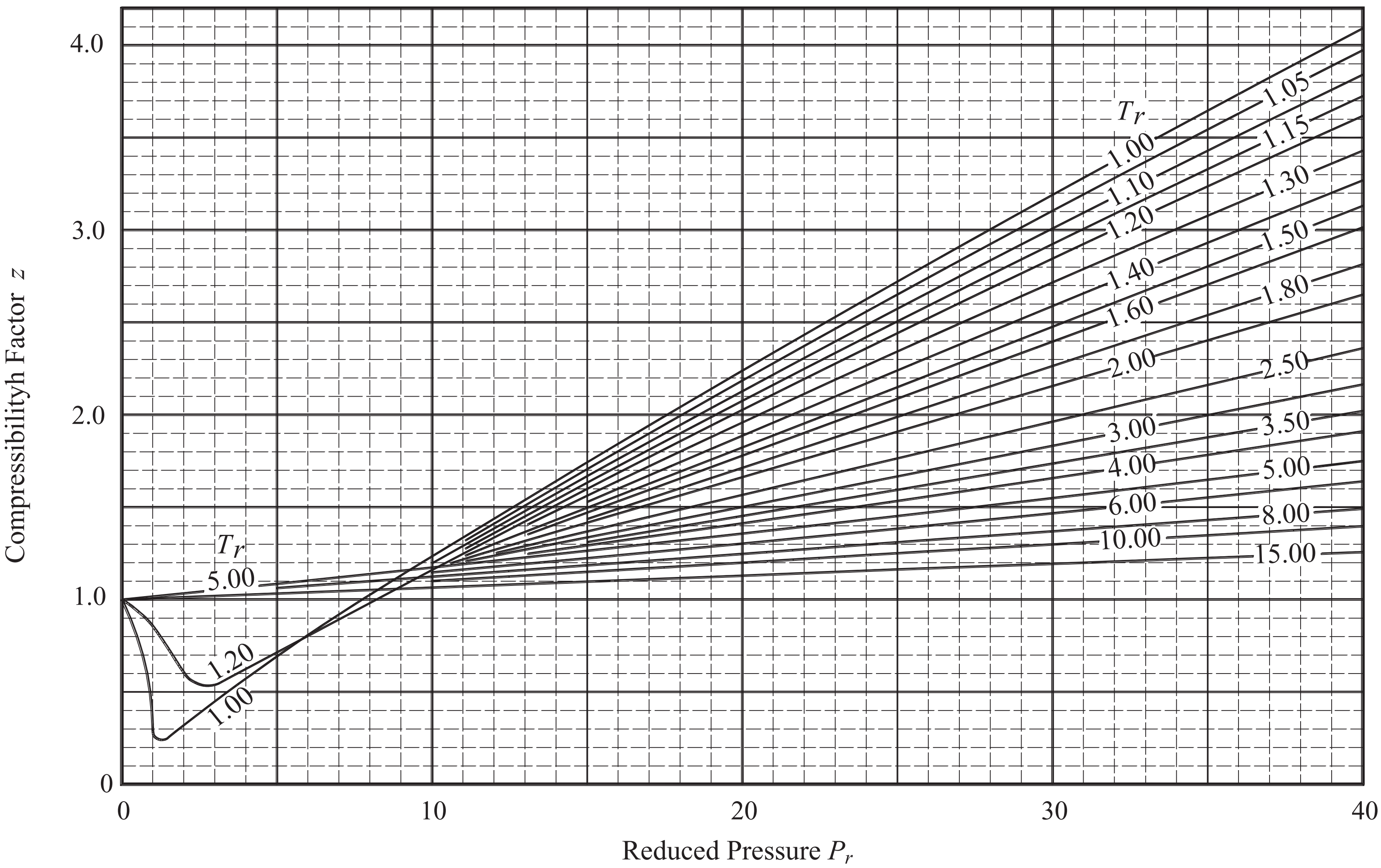

**FIGURE 1.3.** (a) Generalized compressibility factor.

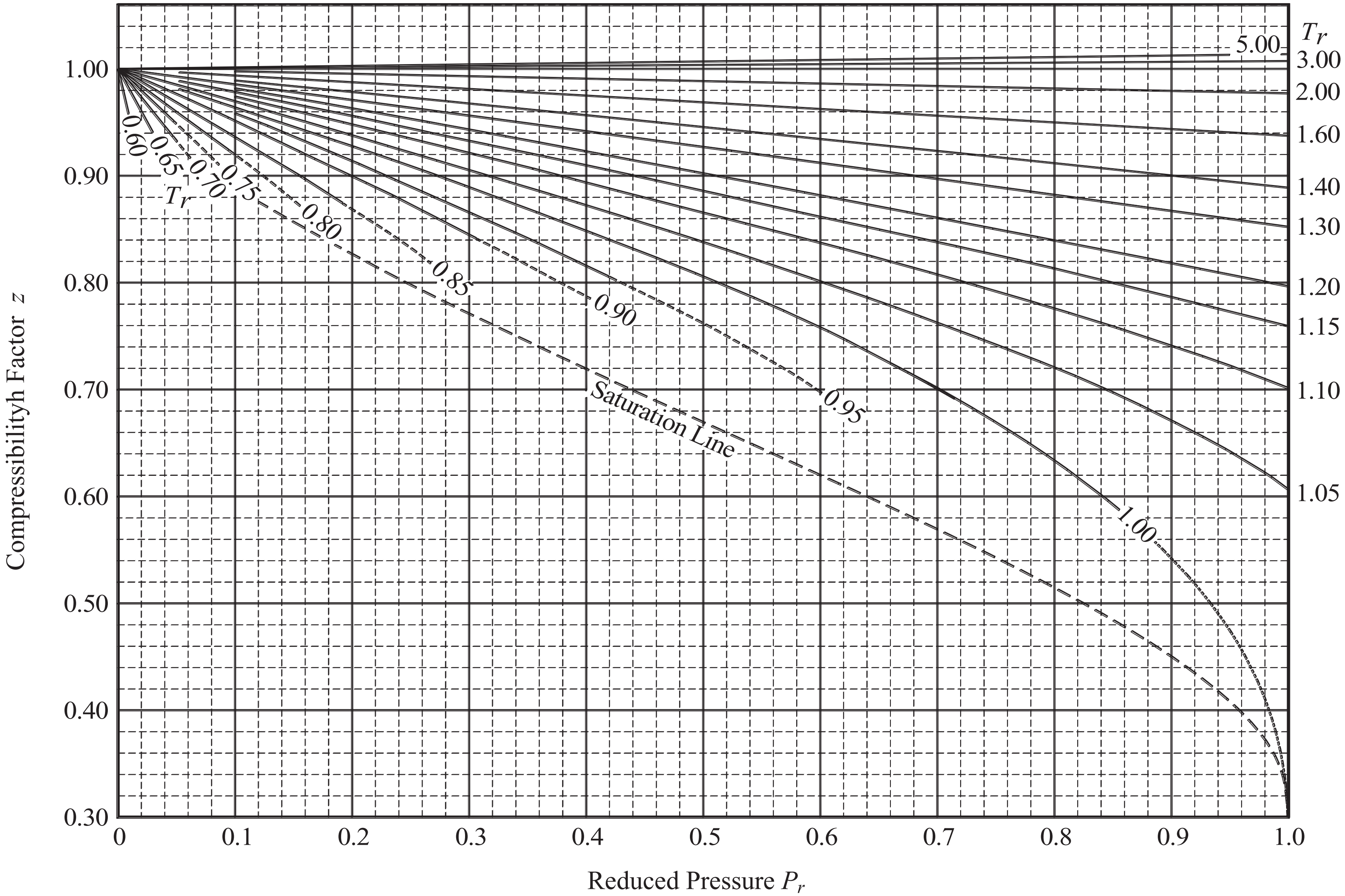

**FIGURE 1.3.** (*Continued*) (b) Generalized compressibility factor—subcritical range.

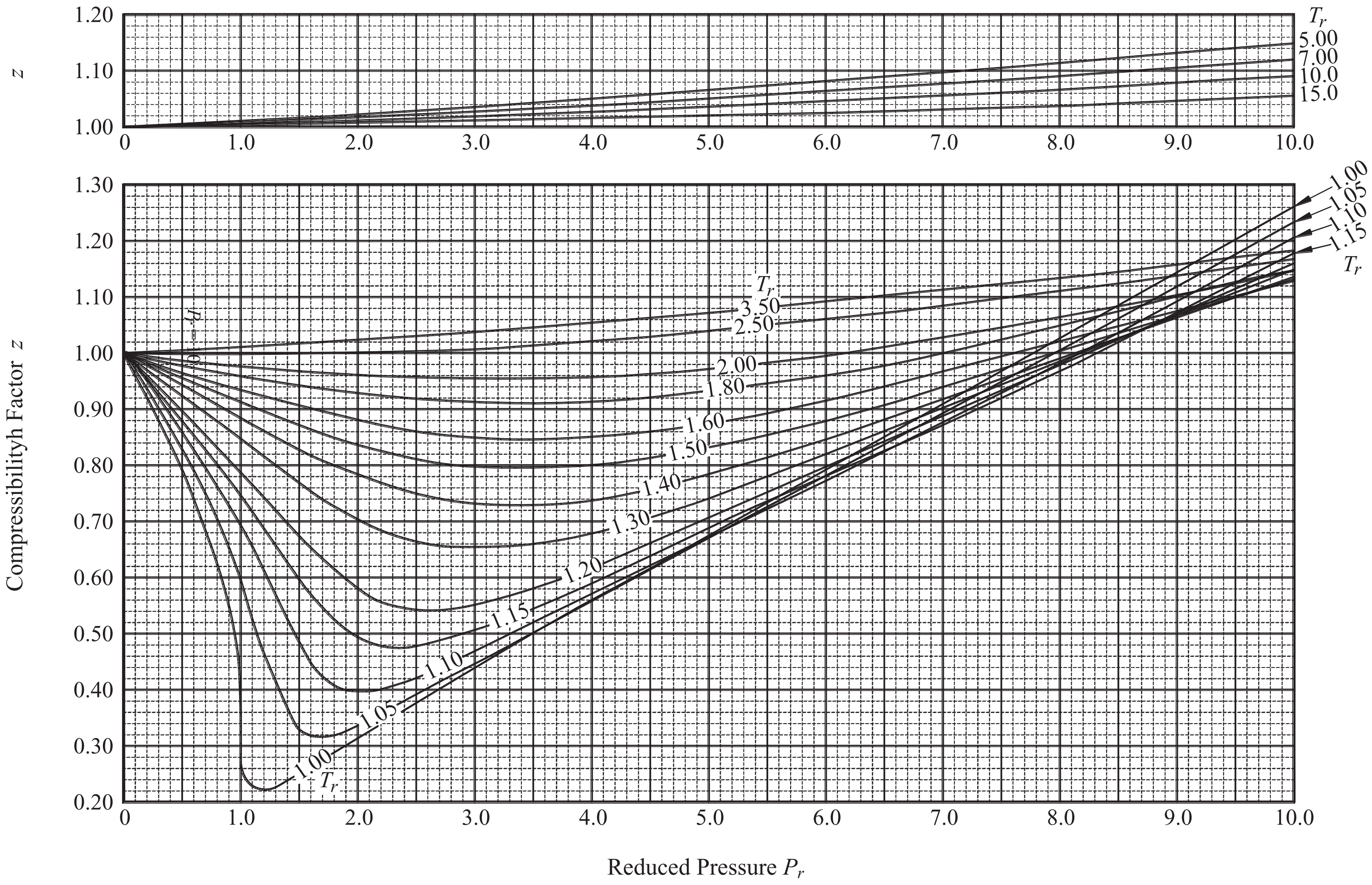

**FIGURE 1.3.** (*Continued*) (c) Generalized compressibility factor—pressure range to $P_r = 10$.

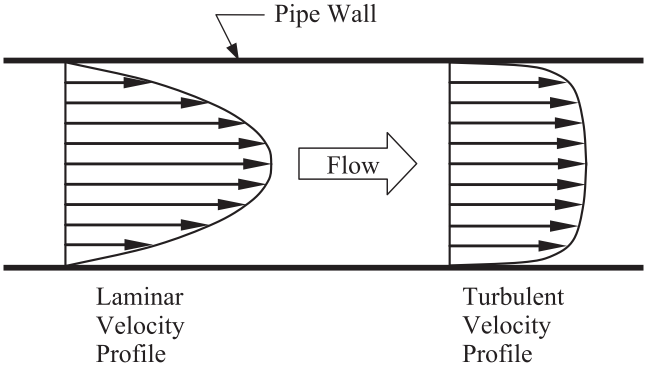

**FIGURE 1.4.** Velocity profiles.

## REFERENCES

1. Graham, L., Heat, thermometry, in *Encyclopedia Britannica*, Vol. 8, 15th ed., Encyclopedia Britannica, 1978, Macropedia, p. 706.
2. Reid, R. C., J. M. Prausnitz, and T. K. Sherwood, *The Properties of Gases and Liquids*, 3rd ed., McGraw-Hill, 1977, p. 81.
3. Poling, B. E., J. M. Prausnitz, and J. P. O'Connell, *Properties of Gases and Liquids*, 5th ed., McGraw-Hill, 2001.
4. Baumeister, T., ed., *Marks' Standard Handbook for Mechanical Engineers*, 8th ed., McGraw-Hill, 1978, pp. 4–17.
5. Nelson, L. C. and E. F. Obert, Generalized pvT properties of gases, *Transactions of the American Society of Mechanical Engineers*, 76, 1954, 1057.

## FURTHER READING

This list includes books and papers that may be helpful to those who wish to pursue further study.

Asimov, I., *Understanding Physics*, Vol. 1. Dorset Press, 1966.

Bedford, R. E., Thermometry, in *Encyclopedia Britannica*, Vol. 18, 15th ed., Encyclopedia Britannica, 1978, p. 322.

Fox, R. W., P. J. Pritchard, and A. T. McDonald, *Introduction to Fluid Mechanics*, 7th ed., John Wiley & Sons, 2008.

Streeter, V. L. and E. B. Wylie, *Fluid Mechanics*, 7th ed., McGraw-Hill, 1979.

Munson, B. R., D. F. Young, and T. H. Okiishi, *Fundamentals of Fluid Mechanics*, 3rd ed., John Wiley & Sons, 1998.