1 Basic Concepts and Fluid Properties

1.1 Introduction

The science of fluid mechanics has matured over the last 200 years, but even today we do not have complete and exact solutions to all possible engineering problems. Although the governing equations (called the Navier–Stokes equations) were established by the mid-1800s, solutions did not follow immediately. The main reason is that it is close to impossible to analytically solve these nonlinear partial differential equations for an arbitrary case. Consequently, the science of fluid mechanics has focused on simplifying this complex mathematical model and on providing partial solutions for more restricted conditions. Therefore the different chapters on classical fluid mechanics are based on retaining different portions of the general equation while neglecting other lower-order terms. This approach allows the solution of the simplified equation, yet preserves the dominant physical effects (relevant to that particular flow regime). Finally, with the enormous development of computational power in the 21st century, numerical solutions of the fluid mechanic equations have become a reality. However, in spite of these advances, elements of modeling are still used in these solutions, and the understanding of the "classical" but limited models is essential for successfully using these modern tools.

This first chapter provides a short introduction on the historical evolution of fluid mechanics and a brief survey of fluid properties. After this introduction, the fluid dynamic equations are developed in the next chapter.

1.2 A Brief History

The science of fluid mechanics is neither new nor biblical; however, most of the progress in this field was made in the 20th century. Therefore it is appropriate to open this text with a brief history of the discipline, with only a very few names mentioned.

As far as we can document history, fluid dynamics and related engineering were always integral parts of human evolution. Ancient civilizations built ships, sails, irrigation systems, and flood-management structures, all requiring some basic understanding of fluid flow. Perhaps the best known early scientist in this field is

Archimedes of Syracuse (287–212 B.C.E.), founder of the field now we call "fluid statics," whose laws on buoyancy and flotation are used to this day.

A major leap in understanding fluid mechanics began with the European Renaissance of the 14th–17th centuries. The famous Italian painter–sculptor, Leonardo da Vinci (1452–1519), was one of the first to document basic laws such as the conservation of mass. He sketched complex flow fields, suggested feasible configurations for airplanes, parachutes, and even helicopters, and introduced the principle of streamlining to reduce drag.

During the next couple of hundred years, the sciences were gradually developed and then suddenly accelerated by the rational mathematical approach of an Englishman, Sir Isaac Newton (1642–1727), to physics. Apart from the basic laws of mechanics, and particularly the second law connecting acceleration with force, the concepts for drag and shear in a moving fluid were developed by Newton, and his principles are widely used today.

The foundations of fluid mechanics really crystallized in the 18th century. One of the more famous scientists, Daniel Bernoulli (1700–1782, Dutch-Swiss), pointed out the relation between velocity and pressure in a moving fluid, an equation that bears his name appears in every textbook. However, his friend Leonhard Euler (1707–1783, Swiss born), a real giant in this field, is the one who actually formulated the Bernoulli equations in the form known today. In addition, Euler, using Newton's principles, developed the continuity and momentum equations for fluid flow. These differential equations, the Euler equations, are the basis for modern fluid dynamics and perhaps the most significant contribution to the process of understanding fluid flows. Although Euler derived the mathematical formulation, he did not provide solutions to his equations. (Note that Euler is pronounced "oiler," not "yuler"; hence we have "*an* Euler equation.")

Science and experimentation in the field increased, but it was only in the 19th century that the governing equations were finalized in the form known today. A Frenchman, Claude-Louis-Marie-Henri Navier (1785–1836), understood that friction in a flowing fluid must be added to the force balance. He incorporated these terms into the Euler equations and published the first version of the complete set of equations in 1822. These equations are known today as the Navier–Stokes equations. Communications and information transfers were not well developed in those days. For example, Sir George Gabriel Stokes (1819–1903) lived on the English side of the English Channel but did not communicate directly with Navier. Independently, he also added the viscosity term to the Euler equations. Hence the glory is shared by both scientists for these equations. Stokes can be also considered the first to solve the equations for the motion of a sphere in a viscous flow, which is now called "Stokes flow."

Although the theoretical basis for the governing equation had been laid down by now, it was clear that the solution was far out of reach. Therefore scientists focused on "approximate models," using only portions of the equation that could be solved. Experimental fluid mechanics also gained momentum, with important discoveries by Englishman Osborne Reynolds (1842–1912) about turbulence and transition from laminar to turbulent flow. This brings us to the 20th century, when science and technology grew at an explosive rate, particularly after the first powered flight of the Wright brothers in the United States (December 1903). Fluid mechanics attracted not only the greatest talent but also investments from governments as the potential of flying machines was recognized. If only one name is mentioned per century, then Ludwig Prandtl (1874–1953) of Göttingen, Germany, deserves the glory for the 20th century. He made tremendous progress in developing simple models for problems such as the flow in boundary layers and over airplane wings.

This trend of solving models and not the complex Navier–Stokes equations continued well into the mid-1990s, until the tremendous growth in computer power finally allowed numerical solutions of these equations. Physical modeling is still required, but the numerical approach allows the solutions of nonlinear partial differential equations, an impossible task from the pure analytical point of view. Nowadays, the flow over complex shapes and the resulting forces can be computed by commercial computer codes, but without being exposed to simple models, our ability to analyze the results would be incomplete.

1.3 Dimensions and Units

The magnitude (or dimensions) of physical variables is expressed in engineering units. In this book we follow the metric system, which was accepted by most professional societies in the mid-1970s. This International system, (SI for Systeme International) of units is based on the decimal system and is much easier to use than other (e.g., British) systems of units. For example the basic length is measured in meters (m): 1000 m is a kilometer (km) and 1/100 of a meter is a centimeter (cm). Along the same line, 1/1000 m is a millimeter (mm).

Mass is measured in grams (g), which is the mass of one cubic centimeter (1 cm^3) of water. One thousand grams are one kilogram (kg), and 1000 kg are one metric ton. Time is still measured the old-fashioned way, in hours (h), 1/60 of an hour is a minute (min), and 1/60 of a minute is a second (s).

For this book, velocity is one of the most important variables, and its basic measure therefore is meters per second (m/s). Vehicle speeds are usually measured in kilometers per hour (km/h) and clearly $1\,\mathrm{km/h} = 1000/3600 = 1/3.6\,\mathrm{m/s}$. Acceleration is the rate of change of velocity and therefore it is measured in meters per second squared (m/s^2).

Newton's second law defines the units for the force F when a mass m is accelerated at a rate of a:

$$F = ma = \mathrm{kg}\frac{\mathrm{m}}{\mathrm{s}^2}.$$

Therefore this unit is called a newton ($\mathrm{N} = \mathrm{kg}\frac{\mathrm{m}}{\mathrm{s}^2}$). Sometimes the unit *kilogram-force* ($\mathrm{kg_f}$) is used because the gravitational pull of 1-kg mass at sea level is 1 $\mathrm{kg_f}$. If we approximate the gravitational acceleration as $g = 9.8\ \mathrm{m/s^2}$, then

$$1\,\mathrm{kg_f} = 9.8\,\mathrm{N}.$$

The pressure, which is the force per unit area, is measured with the previous units,

$$p = \frac{F}{S} = \frac{\mathrm{kg}\cdot\dfrac{\mathrm{m}}{\mathrm{s}^2}}{\mathrm{m}^2} = \frac{\mathrm{N}}{\mathrm{m}^2} = 1\,\mathrm{Pascal\,(Pa)};$$

this unit is named for the French scientist Blaise Pascal (1623–1662). Sometimes an atmosphere (atm) is used to measure pressure, and this unit is about 1 kg_f/cm^2, or, more accurately,

$$1\ \text{atm} = 1.013 \times 10^5\ \text{N/m}^2.$$

In the following sections we discuss some of the more important fluid properties along with the units used to quantify them. In reality, there are a large number of engineering units, and a list of the most common ones is provided in Appendix A.

1.4 Fluid Dynamics and Fluid Properties

Fluid dynamics is the science dealing with the motion of fluids. Fluids, unlike solids, cannot assume a fixed shape under load and will immediately deform. For example, if we place a brick in the backyard pool it will sink because the fluid below is not rigid enough to hold it.

Both gases and liquids behave similarly under load and both are considered fluids. A typical engineering question that we'll try to answer here is this: What are the forces that are due to fluid motion? Examples could focus on estimating the forces required for propelling a ship or for calculating the size and shape of a wing required for lifting an airplane. So let us start with the first question: What is a fluid?

As noted, in general, we refer to liquids and gases as fluids, but we can treat the flow of grain in agricultural machines, a crowd of people leaving a large stadium, or the flow of cars by using the principles of fluid mechanics. Therefore one of the basic features is that we can look at the fluid as a continuum and not analyze each element or molecule (hence the analogy to grain or seeds). The second important feature of fluids is that they deform easily, unlike solids. For example, a static fluid cannot resist a shear force and the particles will simply move. Therefore, to generate shear force, the fluid must be in motion. This is clarified in the following subsections.

1.4.1 Continuum

Most of us are acquainted with Newtonian mechanics, and therefore it would be natural for us to look at particle (or group of particles) motion and discuss their dynamics by using the same approach used in courses such as dynamics. Although this approach has some followers, let us first look at some basics.

Consideration a: The number of molecules is very large and it would be difficult to apply the laws of dynamics, even when a statistical approach is used. For example, the number of molecules in one gram-mole (1 g mole) is called the Avogadro number (after the Italian scientist, Amadeo Avogadro, 1776–1856). 1 g mole is the molecular weight multiplied by 1 g. For example, for a hydrogen molecule (H_2) the molecular weight is 2; therefore 2 g of hydrogen are 1 g mole. The Avogadro number N_A is

$$N_A = 6.02 \times 10^{23} \text{molecules/g mole}. \tag{1.1}$$

Because the number of molecules is very large, it is easier for us to assume a continuous fluid rather than to discuss the dynamics of each molecule or even their dynamics by using a statistical approach.

Consideration b: In gases, which we can view as the least condensed fluids, the particles are far from each other, but as Brown (Robert Brown, botanist, 1773–1858) observed in 1827, the molecules are constantly moving, and hence this phenomenon is called Brownian motion. The particles move at various speeds and in arbitrary directions, and the average distance between particle collisions is called the mean free path λ, which for standard air is about 6×10^{-6} cm. Now, suppose that a pressure disturbance (or a jump in the particle velocity) is introduced; this effect will be communicated to the rest of the fluid by the preceding interparticle collisions. The speed that this disturbance spreads in the fluid is called the speed of sound, and this gives us an estimate about the order of molecular speeds (the speed of sound is about 340 m/s in air at 288 K). Of course, many particles must move faster than this speed because of the three-dimensional (3D) nature of the collisions (see Section 1.6). It is only logical that the speed of sound depends on temperature because temperature is related to the internal energy of the fluid. If this molecular mean-free-path distance λ is much smaller than the characteristic length L in the flow of interest (e.g., $L \sim$ the chord of an airplane's wing) then, for example, we can consider the air (fluid) as a *continuum*! In fact, a nondimensional number, called the Knudsen number (after the Danish scientist Martin Knudsen, 1871–1949), exists based on this relation:

$$\mathrm{Kn} = \frac{\lambda}{L}. \tag{1.2}$$

Thus, if $\mathrm{Kn} < 0.01$, meaning that the characteristic length is 100 times larger than the mean free path, then the continuum assumption may be used. Exceptions for this assumption of course would be when the gas is very rare ($\mathrm{Kn} > 1$), e.g., in vacuum or at very high altitudes in the atmosphere.

Therefore, if we agree on the concept of a continuum, we do not need to trace individual molecules (or groups of molecules) in the fluid but rather we should observe the changes in the average properties. Apart from properties such as density or viscosity, the fluid flow may have certain features that must be clarified early on. Let us first briefly discuss frequently used terms such as laminar and turbulent and attached and separated flows, and then focus on the properties of the fluid material itself.

1.4.2 Laminar and Turbulent Flows

Now that, by means of the continuum assumption, we have eliminated the discussion about arbitrary molecular motion, a somewhat similar but much larger-scale phenomenon must be discussed. For the discussion let us assume a free-stream flow along the x axis with uniform velocity U. If we follow the traces made by several particles in the fluid we would expect to see parallel lines, as shown in the upper part of Fig. 1.1. If, indeed, these lines are parallel and flow in the direction of the average velocity and the motion of the fluid seems to be "well organized," then this flow is called laminar. If we consider a velocity vector in a Cartesian system,

$$\vec{q} = (u, v, w), \tag{1.3}$$

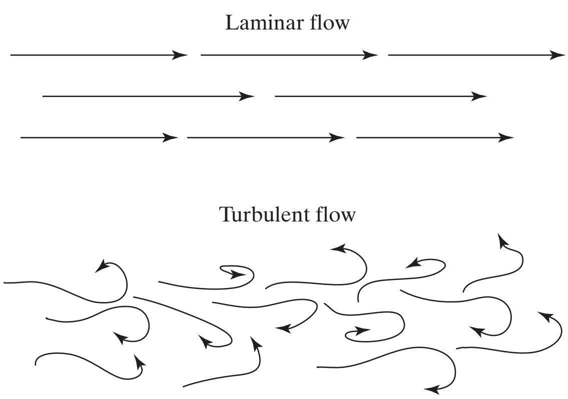

Figure 1.1. Schematic description of laminar and turbulent flows having the same average velocity.

then for this steady-state flow the velocity vector will be

$$\vec{q} = (U, 0, 0), \tag{1.3a}$$

and here U is the velocity in the x direction.

On the other hand, it is possible to have the same average speed in the flow, but in addition to this average speed the fluid particles will momentarily move in the other directions (lower part of Fig. 1.1). The fluid is then called turbulent (even though the average velocity U_{av} could be the same for both the laminar and turbulent flows). In this two-dimensional (2D) case the flow is time dependent everywhere, and the velocity vector then becomes

$$\vec{q} = (U_{\text{av}} + u', v', w'), \tag{1.4}$$

where u', v', and w' are the perturbations in the x, y, and z directions. Also, it is clear that the average velocities in the other directions are zero:

$$V_{\text{av}} = W_{\text{av}} = 0.$$

So if a simple one-dimensional (1D) laminar flow transitions into a turbulent flow, then it also becomes 3D (not to mention time dependent). Knowing whether the flow is laminar or turbulent is very important for most engineering problems because features such as friction and momentum exchange can change significantly between these two types of flow. The fluid flow can become turbulent in numerous situations such as inside long pipes or near the surface of high-speed vehicles.

1.4.3 Attached and Separated Flows

By observing several streamline traces in the flow (by injecting smoke, for example), we can see if the flow follows the shape of an object (e.g., a vehicle's body) close to its surface. When the streamlines near the solid surface follow exactly the shape of the body [as in Fig. 1.2(a)], the flow is considered to be attached. If the flow does not follow the shape of the surface [as seen behind the vehicle in Fig. 1.2(b)], then the flow is considered detached or separated. Usually such separated flows behind the vehicle will result in an unsteady wake flow, which can be felt up to large distances behind the vehicle. Also, in Fig. 1.2(b) the flow is attached on the upper surface and is separated only behind the vehicle. As we shall see later, having attached flow fields is extremely important because the vehicle with the larger areas of flow separation

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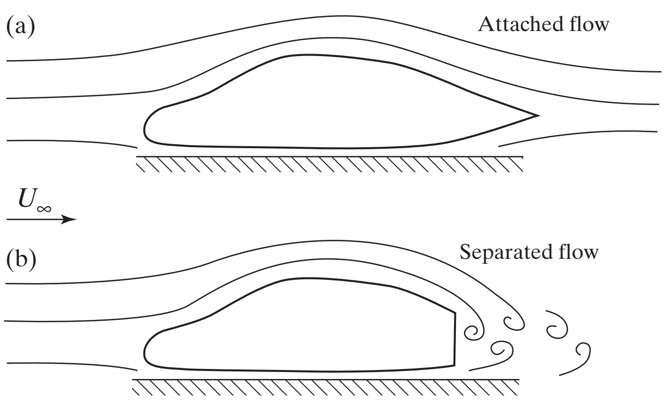


Figure 1.2. (a) Attached flow over a streamlined car and (b) the locally separated flow behind a more realistic automobile shape.

is likely to experience higher resistance (drag). Now, to complicate matters, if the flow above this model is turbulent then, because of the momentum influx from the outer fluid layers, the flow separation can be delayed.

1.5 Properties of Fluids

Fluids, in general, may have many properties related to thermodynamics, mechanics, or other fields of science. In the following subsections, only a few, which are used in introductory fluid mechanics, are mentioned.

1.5.1 Density

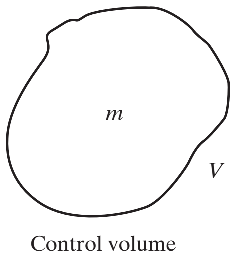
Density, by definition, is mass per unit volume. In the case of fluids, we can define the density (with the aid of Fig. 1.3) as the limit of this ratio when a measuring volume V shrinks to zero. We need to use this definition because density can change from one point to the other. Also in this picture, we can relate to a volume element in space that we can call "control volume," which moves with the fluid or can be stationary (in any case it is better to place this control volume in inertial frames of reference).

Therefore the definition of density at a point is

$$\rho = \lim_{V \to 0} \left(\frac{m}{V} \right). \tag{1.5}$$

Typical units are kilograms per cubic meter (kg/m^3) or grams per cubic centimeter (g/cm^3).

Figure 1.3. Mass m in a control volume V. Density is the ratio of m/V.



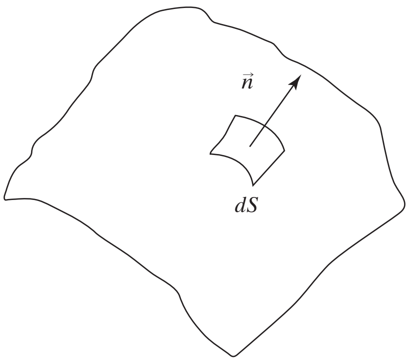


Figure 1.4. Pressure acts normal to the surface dS ($\vec{n}$ is the unit vector normal to the surface).

1.5.2 Pressure

We can describe the pressure p as the normal force F per unit area acting on a surface S. Again, we use the limit process to define pressure at a point, as it may vary on a surface:

$$p = \lim_{S \to 0} \left(\frac{F}{S} \right). \tag{1.6}$$

Bernoulli pictured the pressure as being a result of molecules impinging on a surface (so this force per area is a result of the continuous bombardment of the molecules). Therefore, the fluid pressure acting on a solid surface is normal to the surface, as shown in Fig. 1.4. Consequently the force direction is obtained by multiplying with the unit vector $\vec{n}$ normal to the surface. Because the pressure acts *normal* to a surface the resulting ΔF force is

$$\Delta F = -p\vec{n}\, ds. \tag{1.7}$$

Here the minus sign is a result of the normal unit vector pointing outside the surface while the force that is due to pressure points inward. Also note that the pressure at a point inside a fluid is the same in all directions. This property of the pressure is called *isetropic*. The observation about the fluid pressure at a point acting equally in any arbitrary direction was documented first by Blaise Pascal (1623–1662).

The units used for pressure were introduced in Section 1.3. However, the pascal is a small unit; the units used more often are the kilopascal (kP), the atmosphere (atm), or the bar (bar has no abbreviation; hence the correct use is: 1 bar or 5 bars):

$$1\,\mathrm{kP} = 1000\frac{\mathrm{N}}{\mathrm{m}^2}, \qquad 1\,\mathrm{atm} = 101{,}300\frac{\mathrm{N}}{\mathrm{m}^2}, \qquad 1\,\mathrm{bar} = 100{,}000\frac{\mathrm{N}}{\mathrm{m}^2}.$$

1.5.3 Temperature

Temperature is a measure of the internal energy at a point in the fluid. Over the years different methods have evolved to measure temperature; for example, the freezing point of water is considered zero in the Celsius system and the boiling temperature of water under standard conditions is 100 °C. Kelvin units (K) are similar to Celsius; however, they measure the temperature from absolute zero, a temperature found in space, and they represent a condition when molecular motion will stop. The relation between the two temperature-measuring systems is

$$\mathrm{K} = 273.16 + {}^\circ\mathrm{C}. \tag{1.8}$$

The Celsius system is widely used in European countries whereas in the United States, Fahrenheit units are still used. In this case, 100 °F was set to be close to the human body's temperature. The conversion between these temperature-measuring systems is

$$^\circ\mathrm{C} = 5/9(^\circ\mathrm{F} - 32), \tag{1.9}$$

which indicates that $0\,^\circ\mathrm{C} = 32\,^\circ\mathrm{F}$. The absolute temperature in these units is in Rankine units (°R) and this scale is higher by 459.69°:

$$^\circ\mathrm{R} = 459.69 + {}^\circ\mathrm{F}. \tag{1.10}$$

Now that we have introduced density, pressure, and temperature, it is important to recall the ideal-gas relation, in which these properties are linked together by the gas constant R:

$$p/\rho = RT. \tag{1.11}$$

If we define v as the volume per unit mass then $v = 1/\rho$, and we can write

$$pv = RT. \tag{1.12}$$

However, R is different for various gases or for their mixtures, but it can be easily calculated with the universal gas constant $\mathcal{R}$ ($\mathcal{R} = 8314.3$ J/mol K). Then we can find R by dividing this universal $\mathcal{R}$ by the average molecular weight M of the mixture of gases.

EXAMPLE 1.1. THE IDEAL-GAS FORMULA. As an example, for air we can assume $M = 29$ and therefore

$$R = \mathcal{R}/M = 8314.3/29 = 286.7\,\mathrm{m^2/(s^2\ K)} \text{ for air.} \tag{1.13}$$

Suppose we want to calculate the density of air when the temperature is 300 K and the pressure is 1 $\mathrm{kg_f/cm^2}$:

$$\rho = p/RT = 1 \times 9.8 \times 10^4/286.7 \times 300 = 1.139\,\mathrm{kg/m^3}.$$

Here we used $1\,\mathrm{kg_f/cm^2} = 9.8 \times 10^4\,\mathrm{N/m^2}$ and $g = 9.8\,\mathrm{m/s^2}$.

Another interesting use of the universal gas constant is when we can calculate the volume (V) of 1 g mole of gas in the following conditions (e.g., $T = 300$ K and $p = 1\,\mathrm{atm} = 101{,}300\,\mathrm{N/m^2}$). For air we should take 29 g because $M = 29$ and therefore $\mathcal{R}$ is multiplied by 10^{-3} because we considered 1 g mole and not 1 kg mole:

$$V = \mathcal{R}T/p = 8314.3 \times 10^{-3} \times 300/101{,}300 = 24.62 \times 10^{-3}\,\mathrm{m^3} = 24.62\,\mathrm{L}.$$

Note that 1 g mole of any gas will occupy the same volume because we have the same number of molecules (as postulated by Avogadro). Also, L is one liter ($= 0.001\,\mathrm{m^3}$).

1.5.4 Viscosity

The viscosity is a very important property of fluids, particularly when fluid motion is discussed. In fact, the schematic diagram of Fig. 1.5 is often used to demonstrate the

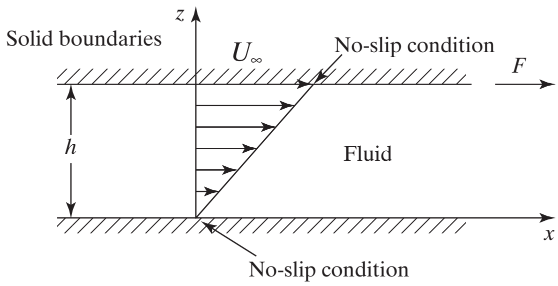


Figure 1.5. The flow between two parallel plates. The lower is stationary while the upper moves at a velocity of U_∞.

difference between solids and fluids. A fluid must be in motion in order to generate a shear force, whereas a solid can support shear forces in a stationary condition.

In this figure the upper plate moves at a velocity of U_∞ while the lower surface is at rest. A fluid is placed between these parallel plates, and when the upper plate is pulled, a force F is needed. At this point we can make another important observation. The fluid particles in immediate contact with the plates will not move relative to the plates (as if they were glued to it). This is called the *no-slip boundary condition*, and we will use this in later chapters. Consequently we can expect the upper particles to move at the upper plate's speed while the lowest fluid particles attached to the lower plate will be at rest. Newton's law of friction states that

$$\tau = \mu \frac{dU}{dz}. \tag{1.14}$$

Here τ is the shear force per unit area (shear stress) and μ is the fluid viscosity. In this case the resulting velocity distribution is linear and the shear will be constant inside the fluid (for $h > z > 0$). For this particular case we can write

$$\tau = \mu \frac{U_\infty}{h}. \tag{1.15}$$

A fluid that behaves like this is called a Newtonian fluid, indicating a linear relation between the stress and the strain. As noted earlier, this is an important property of fluids because without motion there is no shear force.

The units used for τ are force per unit area, and the units for the viscosity μ are defined by Eq. (1.14). Some frequently used properties of some common fluids are provided in Table 1.1.

Table 1.1. *Approximate properties of some common fluids at 20 °C (ρ = density, μ = viscosity, σ = surface tension)*

Fluid	ρ (kg/m^3)	μ (N s/m^2)	σ (N/m)
Air	1.22	1.8×10^{-5}	
Helium	0.179	1.9×10^{-5}	
Gasoline	680	3.1×10^{-4}	2.2×10^{-2}
Kerosene	814	1.9×10^{-3}	2.8×10^{-2}
Water	1000	1.0×10^{-3}	7.3×10^{-2}
Sea water	1030	1.2×10^{-3}	7.3×10^{-2}
Motor oil (SAE 30)	919	0.29	3.6×10^{-2}
Glycerin	1254	0.62	6.3×10^{-2}
Mercury	13600	1.6×10^{-3}	4.7×10^{-1}