GLOSSARY

Guest Author: James G. Brasseur, The Pennsylvania State University

Note: **Boldface color** glossary terms correspond to **boldface color** terms in the text. The number in [square brackets] denotes the page of the boldface color term in the text. *Italics* indicates a term defined elsewhere in the glossary.

Boldface terms without page numbers are concepts that are not defined in the text but are defined or cross-referenced in the glossary for students to review.

absolute pressure [66]: See *stress, pressure stress.* Contrast with *gage pressure.*

absolute viscosity [47]: See *viscosity.*

acceleration field [122]: See *field.*

adiabatic process [202]: A process with no heat transfer.

advective acceleration [126]: In order to reduce confusion of terminology in flows where *buoyancy forces* generate convective fluid motions, the term "convective acceleration" is often replaced with the term "advective acceleration."

aerodynamics [2]: The application of *fluid dynamics* to air, land, and water-going vehicles. Often the term is specifically applied to the flow surrounding, and forces and moments on, flight vehicles in air, as opposed to vehicles in water or other liquids (*hydrodynamics*).

angle of attack [570]: The angle between an airfoil or wing and the free-stream flow velocity vector.

average: An area/volume/time average of a fluid property is the integral of the property over an area/volume/time period divided by the corresponding area/volume/time period. Also called *mean*.

axisymmetric flow [419, 490, 492, 565]: A flow that when specified appropriately using cylindrical coordinates (r, θ, x) does not vary in the azimuthal (θ) direction. Thus, all partial derivatives in θ are zero. The flow is therefore either one-dimensional or two-dimensional (see also *dimensionality* and *planar flow*).

barometer [75]: A device that measures atmospheric pressure.

basic dimensions: See *dimensions.*

Bernoulli equation [185, 187, 208, 270]: A useful reduction of *conservation of momentum* (and *conservation of energy*) that describes a balance between pressure (*flow work*), velocity (*kinetic energy*), and position of *fluid particles* relative to the gravity vector (potential energy) in regions of a fluid flow where frictional force on fluid particles is negligible compared to pressure force in that region of the flow (see *inviscid flow*). There are multiple forms of the Bernoulli equation for incompressible vs. compressible, steady vs. nonsteady, and derivations through *Newton's law* vs. the *first law of thermodynamics.* The most commonly used forms are for steady incompressible fluid flow derived through conservation of momentum.

bluff (or blunt) body [563]: A moving object with a blunt rear portion. Bluff bodies have *wakes* resulting from massive *flow separation* over the rear of the body.

boundary condition [400, 440]: In solving for flow field variables (velocity, temperature) from governing equations, it is necessary to mathematically specify a function of the variable at the surface. These mathematical statements are called boundary conditions. The no-slip condition that the flow velocity must equal the surface velocity at the surface is an example of a boundary condition that is used with the Navier–Stokes equation to solve for the velocity field.

boundary layer [6, 325, 481, 511]: At high *Reynolds numbers* relatively thin "boundary layers" exist in the flow adjacent to surfaces where the flow is brought to rest (see *no-slip condition*). Boundary layers are characterized by high *shear* with the highest velocities away from the surface. *Frictional force, viscous stress,* and *vorticity* are significant in boundary layers. The approximate form of the two components of the Navier– Stokes equation, simplified by neglecting the terms that are small within the boundary layer, are called the *boundary layer equations.* The associated approximation based on the existence of thin boundary layers surrounded by *irrotational* or *inviscid* flow is called the *boundary layer approximation.*

boundary layer approximation [511]: See *boundary layer.*

boundary layer equations [511, 515]: See *boundary layer.*

boundary layer thickness measures: Different measures of the thickness of a boundary layer as a function of downstream distance are used in fluid flow analyses. These are:

> **boundary layer thickness** [512]: The full thickness of the viscous layer that defines the boundary layer, from the surface to the edge. Defining the edge is difficult to do precisely, so the "edge" of the boundary layer is often defined as the point where the boundary layer velocity is a large fraction of the free-stream velocity (e.g., δ_{99} is the distance from the surface to the point where the streamwise velocity component is 99 percent of the free-stream velocity).
>
> **displacement thickness** [524]: A boundary layer thickness measure that quantifies the deflection of fluid

---

Note: This glossary covers **boldface color terms** found in Chapters 1 to 11.

streamlines in the direction away from the surface as a result of friction-induced reduction in mass flow adjacent to the surface. Displacement thickness (δ^*) is a measure of the thickness of this mass flow rate deficit layer. In all boundary layers, $\delta^* < \delta$.

momentum thickness [527]: A measure of the layer of highest deficit in momentum flow rate adjacent to the surface as a result of frictional resisting force (shear stress). Because Newton's second law states that force equals time rate of momentum change, momentum thickness θ is proportional to surface shear stress. In all boundary layers, $\theta < \delta^*$.

Buckingham Pi theorem [282]: A mathematical theorem used in *dimensional analysis* that predicts the number of nondimensional groups that must be functionally related from a set of dimensional parameters that are thought to be functionally related.

buffer layer [338, 580]: The part of a turbulent boundary layer, close to the wall, lying between the *viscous* and *inertial sublayers.* This thin layer is a transition from the friction-dominated layer adjacent to the wall where *viscous stresses* are large, to the inertial layer where *turbulent stresses* are large compared to viscous stresses.

bulk modulus of elasticity [42]: See *compressibility.*

buoyant force [89]: The net upward hydrostatic pressure force acting on an object submerged, or partially submerged, in a fluid.

cavitation [40]: The formation of vapor bubbles in a liquid as a result of pressure going below the *vapor pressure.*

center of pressure [79, 81]: The effective point of application of pressure distributed over a surface. This is the point where a counteracting force (equal to integrated pressure) must be placed for the net moment from pressure about that point to be zero.

centripetal acceleration [250]: Acceleration associated with the change in the direction of the velocity (vector) of a material particle.

closed system [14, 148]: See *system.*

coefficient of compressibility [42, 55]: See *compressibility.*

compressibility: The extent to which a *fluid particle* changes volume when subjected to either a change in pressure or a change in temperature.

bulk modulus of elasticity [42, 55]: Synonymous with *coefficient of compressibility.*

coefficient of compressibility [42, 55]: The ratio of pressure change to relative change in volume of a *fluid particle.* This coefficient quantifies compressibility in response to pressure change, an important effect in high Mach number flows.

coefficient of volume expansion [44]: The ratio of relative density change to change in temperature of a *fluid particle.* This coefficient quantifies compressibility in response to temperature change.

computational fluid dynamics (CFD) [129, 296, 434]: The application of the conservation laws with boundary and initial conditions in mathematical discretized form to estimate field variables quantitatively on a discretized grid (or mesh) spanning part of the flow field.

conservation laws [172]: The fundamental principles upon which all engineering analysis is based, whereby the material properties of mass, momentum, energy, and entropy can change only in balance with other physical properties involving forces, work, and *heat transfer.* These laws are predictive when written in mathematical form and appropriately combined with boundary conditions, initial conditions, and constitutive relationships.

conservation of energy principle [201]: This is the *first law of thermodynamics,* a fundamental law of physics stating that the time rate of change of total *energy* of a fixed mass (*system*) is balanced by the net rate at which *work* is done on the mass and *heat energy* is transferred to the mass.

Note: To mathematically convert the time derivative of mass, momentum, and energy of fluid mass in a system to that in a *control volume,* one applies the *Reynolds transport theorem.*

conservation of mass principle [175]: A fundamental law of physics stating that a volume always containing the same atoms and molecules (*system*) must always contain the same mass. Thus the time rate of change of mass of a system is zero. This law of physics must be revised when matter moves at speeds approaching the speed of light so that mass and energy can be exchanged as per Einstein's laws of relativity.

conservation of momentum: This is *Newton's second law* of motion, a fundamental law of physics stating that the time rate of change of momentum of a fixed mass (*system*) is balanced by the net sum of all forces applied to the mass.

constitutive equations [426]: An empirical relationship between a physical variable in a *conservation law of physics* and other physical variables in the equation that are to be predicted. For example, the energy equation written for temperature includes the *heat* flux vector. It is known from experiments that heat flux for most common materials is accurately approximated as proportional to the gradient in temperature (this is called Fourier's law). In *Newton's law* written for a *fluid particle,* the *viscous stress tensor* (see *stress*) must be written as a function of velocity to solve the equation. The most common constitutive relationship for viscous stress is that for a *Newtonian fluid.* See also *rheology.*

continuity equation [404]: Mathematical form of *conservation of mass* applied to a *fluid particle* in a flow.

continuum [36, 122]: Treatment of matter as a continuous (without holes) distribution of finite mass *differential volume* elements. Each volume element must contain huge numbers of molecules so that the macroscopic effect of the molecules can be modeled without considering individual molecules.

contour plot [138]: Also called an *isocontour plot,* this is a way of plotting data as lines of constant variable through a flow *field. Streamlines,* for example, may be identified as lines of constant *stream function* in *two-dimensional* incompressible steady flows.

control mass [14]: See *system.*

control volume [14, 122, 148]: A volume specified for analysis where flow enters and/or exits through some portion(s) of the volume surface. Also called an *open system* (see *system*).

convective acceleration [126]: Synonymous with *advective acceleration,* this term must be added to the partial time derivative of velocity to properly quantify the acceleration of a *fluid particle* within an *Eulerian* frame of reference. For example, a fluid particle moving through a contraction in a *steady flow* speeds up as it moves, yet the time derivative is zero. The additional convective acceleration term required to quantify fluid acceleration (e.g., in *Newton's second law*) is called the *convective derivative.* See also *Eulerian description, Lagrangian description, material derivative,* and *steady flow.*

convective derivative: See *material derivative* and *convective acceleration.*

creeping flow [313, 476, 574]: Fluid flow in which frictional forces dominate fluid accelerations to the point that the flow can be well modeled with the acceleration term in Newton's second law set to zero. Such flows are characterized by Reynolds numbers that are small compared to 1 ($\text{Re} \ll 1$). Since Reynolds number typically can be written as characteristic velocity times characteristic length divided by kinematic viscosity (VL/ν), creeping flows are often slow-moving flows around very small objects (e.g., sedimentation of dust particles in air or motion of spermatozoa in water), or with very viscous fluids (e.g., glacier and tar flows). Also called Stokes flow.

deformation rate [139]: See *strain rate.*

derived dimensions [15]: See *dimensions.*

deviatoric stress tensor [427]: Another term for *viscous stress tensor.* See *stress.*

differential analysis [400]: Analysis at a point in the flow (as opposed to over a *control volume*).

differential volume/area/length: A small volume δV, area δA, or length δx in the limit of the volume/area/length shrinking to a point. Derivatives are often produced in this limit. (Note that δ is sometimes written as Δ or d.)

dimensional analysis [277]: A process of analysis based solely on the variables of relevance to the flow system under study, the dimensions of the variables, and dimensional homogeneity. After determining the other variables on which a variable of interest depends (e.g., drag on a car depends on the speed and size of the car, fluid viscosity, fluid density, and surface roughness), one applies the principle of dimensional homogeneity with the *Buckingham Pi theorem* to relate an appropriately nondimensionalized variable of interest (e.g., drag) with the other variables appropriately nondimensionalized (e.g., Reynolds numbers, roughness ratio, and Mach number).

dimensional homogeneity [273]: The requirement that summed terms must have the same *dimensions* (e.g., ρV^2, pressure P, and shear stress τ_{xy} are dimensionally homogeneous while *power,* specific enthalpy h, and $P\dot{m}$ are not). Dimensional homogeneity is the basis of *dimensional analysis.*

dimensionality: The number of spatial coordinates in whose direction velocity components and/or other variables vary for a specified coordinate system. For example, *fully developed* flow in a tube is one-dimensional (1-D) in the radial direction r since the only nonzero velocity component (the axial, or x-, component) is constant in the x- and θ-directions, but varies in the r-direction. *Planar flows* are two-dimensional (2-D). Flows over *bluff bodies* such as cars, airplanes, and buildings are three-dimensional (3-D). Spatial derivatives are nonzero only in the directions of dimensionality.

dimensions [15, 270]: The required specification of a physical quantity beyond its numerical value. See also *units.*

- **derived (or secondary) dimensions** [15]: Combinations of fundamental dimensions. Examples of derived dimensions are: velocity (L/t), stress or pressure ($\text{F/L}^2 = \text{m/(Lt}^2)$), energy or work ($\text{mL}^2/\text{t}^2 = \text{FL}$), density ($\text{m/L}^3$), specific weight ($\text{F/L}^3$), and specific gravity (unitless).
- **fundamental (primary, basic) dimensions** [15, 270]: Mass (m), length (L), time (t), temperature (T), electrical current (I), amount of light (C), and amount of matter (N) without reference to a specific system of units. Note that the force dimension is obtained through Newton's law as $\text{F} = \text{mL/t}^2$ (thus, the mass dimension can be replaced with a force dimension by replacing m with Ft^2/L).

drag coefficient [483, 565]: Nondimensional drag given by the *drag force* on an object nondimensionalized by *dynamic pressure* of the free-stream flow times frontal area of the object:

$$C_D \equiv \frac{F_D}{\frac{1}{2}\rho V^2 A}$$

Note that at high Reynolds numbers ($\text{Re} \gg 1$), C_D is a normalized variable, whereas at $\text{Re} \ll 1$, C_D is nondimensional but is not normalized (see *normalization*). See also *lift coefficient.*

drag force [46, 566]: The force on an object opposing the motion of the object. In a frame of reference moving with the object, this is the force on the object in the direction of flow. There are multiple components to drag force:

friction drag [570]: The part of the drag on an object resulting from integrated surface *shear stress* in the direction of flow relative to the object.

induced drag: The component of the drag force on a finite-span wing that is "induced" by lift and associated with the *tip vortices* that form at the tips of the wing and "downwash" behind the wing.

pressure (or **form**) **drag** [570]: The part of the drag on an object resulting from integrated surface *pressure* in the direction of flow relative to the object. Larger pressure on the front of a moving *bluff body* (such as a car) relative to the rear results from massive *flow separation* and *wake* formation at the rear.

dynamic pressure [189, 565]: When the *Bernoulli equation* in *incompressible steady flow* and/or the *conservation of energy* equation along a streamline are written in forms where each term in the equations has the *dimensions* force/area, dynamic pressure is the *kinetic energy* (per unit volume) term (i.e., $\frac{1}{2}\rho V^2$).

dynamic similarity [278]: See *similarity.*

dynamic viscosity [47]: See *viscosity.*

dynamics [2]: When contrasted with *statics* the term refers to the application of Newton's second law of motion to moving matter. When contrasted with *kinematics* the term refers to forces or accelerations through Newton's law force balances.

eddy viscosity [337]: See *turbulence models.*

efficiency [184]: A ratio that describes levels of losses of useful power obtained from a device. Efficiency of 1 implies no losses in the particular function of the device for which a particular definition of efficiency is designed. For example, mechanical efficiency of a pump is defined as the ratio of useful mechanical power transferred to the flow by the pump to the mechanical energy, or shaft work, required to drive the pump. Pump-motor efficiency of a pump is defined as the ratio of useful mechanical power transferred to the flow over the electrical power required to drive the pump. Pump-motor efficiency, therefore, includes additional losses and is thus lower than mechanical pump efficiency.

energy [41]: A state of matter described by the first law of thermodynamics that can be altered at the macroscopic level by work, and at the microscopic level through adjustments in thermal energy.

flow energy [180]: Synonymous with *flow work.* The work associated with *pressure* acting on a flowing *fluid.*

heat (transfer) [41]: The term "heat" is generally used synonymously with *thermal energy.* Heat transfer is the transfer of thermal energy from one physical location to another.

internal energy [41]: Forms of energy arising from the microscopic motions of molecules and atoms, and from the structure and motions of the subatomic particles comprising the atoms and molecules, within matter.

kinetic energy [41]: Macroscopic (or mechanical) form of energy arising from the speed of matter relative to an inertial frame of reference.

mechanical energy [182]: The nonthermal components of energy; examples include kinetic and potential energy.

potential energy [41]: A mechanical form of energy that changes as a result of macroscopic displacement of matter relative to the gravitational vector.

thermal energy [41]: Internal energy associated with microscopic motions of molecules and atoms. For single-phase systems, it is the energy represented by temperature.

total energy [41]: Sum of all forms of energy. Total energy is the sum of kinetic, potential, and internal energies. Equivalently, total energy is the sum of mechanical and thermal energies.

work energy [204]: The integral of force over the distance in which a mass is moved by the force. Work is energy associated with the movement of matter by a force.

energy grade line [193]: See *grade lines.*

English system [15]: See *units.*

entry length [327]: The entry flow region in a pipe or duct flow where the wall boundary layers are thickening toward the center with axial distance *x* of the duct, so that axial derivatives are nonzero. As with the *fully developed* region, the *hydrodynamic entry length* involves growth of a velocity boundary layer, and the *thermal entry length* involves growth of a temperature boundary layer.

Eulerian derivative [127]: See *material derivative.*

Eulerian description [122]: In contrast with a *Lagrangian description,* an Eulerian analysis of fluid flow is developed from a frame of reference through which the *fluid particle*s move. In this frame the acceleration of fluid particles is not simply the time derivative of fluid velocity, and must include another term, called *convective acceleration,* to describe the change in velocity of fluid particles as they move through a *velocity field.* Note that velocity fields are always defined in an Eulerian frame of reference.

extensional strain rate [139]: See *strain rate.*

extensive property [36, 150]: A fluid property that depends on total volume or total mass (e.g., total internal energy). See *intensive property.*

field [124]: The representation of a flow variable as a function of Eulerian coordinates (x, y, z). For example, the *velocity* and *acceleration fields* are the fluid velocity and acceleration vectors $(\vec{V}, \vec{a})$ as functions of position (x, y, z) in the *Eulerian description* at a specified time t.

flow field [123]: The field of flow variables. Generally, this term refers to the velocity field, but it may also mean all field variables in a fluid flow.

first law of thermodynamics [201]: See *conservation laws, conservation of energy.*

flow separation [6, 569]: A phenomenon where a *boundary layer* adjacent to a surface is forced to leave, or "separate" from, the surface due to "adverse" pressure forces (i.e., increasing pressure) in the flow direction. Flow separation occurs in regions of high surface curvature, for example, at the rear of an automobile and other bluff bodies.

flow work [205]: The work term in *first law of thermodynamics* applied to fluid flow associated with pressure forces on the flow. See *energy, flow energy.*

fluid [2]: A material that when sheared deforms continuously in time during the period that shear forces are applied. By contrast, shear forces applied to a *solid* cause the material either to deform to a fixed static position (after which deformation stops), or cause the material to fracture. Consequently, whereas solid deformations are generally analyzed using strain and shear, fluid flows are analyzed using rates of strain and shear (see *strain rate*).

fluid mechanics/dynamics [2]: The study and analysis of fluids through the macroscopic conservation laws of physics, i.e., conservation of mass, momentum (*Newton's second law*), and energy (first law of thermodynamics), and the second law of thermodynamics.

fluid particle/element [124]: A *differential* particle, or element, embedded in a fluid flow containing always the same atoms and molecules. Thus a fluid particle has fixed mass δm and moves with the flow with local flow velocity $\vec{V}$, acceleration $\vec{a}_{\text{particle}} = D\vec{V}/Dt$ and trajectory ($x_{\text{particle}}(t)$, $y_{\text{particle}}(t)$, $t_{\text{particle}}(t)$). See also *material derivative, material particle, material position vector,* and *pathline.*

forced flow [11]: Flow resulting from an externally applied force. Examples include liquid flow through tubes driven by a pump and fan-driven airflow for cooling computer components. *Natural flows,* in contrast, result from internal buoyancy forces driven by temperature (i.e., density) variations within a fluid in the presence of a gravitational field. Examples include buoyant plumes around a human body or in the atmosphere.

friction/frictional: See *Newtonian fluid, viscosity,* and *viscous force.*

friction factor [331]: It can be shown from *dimensional analysis* and *conservation of momentum* applied to a *steady fully developed* pipe flow that the frictional contribution to the pressure drop along the pipe, nondimensionalized by flow *dynamic pressure* ($\frac{1}{2}\rho V^2_{\text{avg}}$), is proportional to the length-to-diameter ratio (L/D) of the pipe. The proportionality factor f is called the friction factor. The friction factor is quantified from experiment (turbulent flow) and theory (laminar flow) in empirical relationships, and in the *Moody chart,* as a function of the Reynolds number and nondimensional roughness. Conservation of momentum shows that the friction factor is proportional to the nondimensional wall shear stress (i.e., the *skin friction*).

frictionless flow [191]: Mathematical treatments of fluid flows sometimes use conservation of momentum and energy equations without the frictional terms. Such mathematical treatments "assume" that the flow is "frictionless," implying no *viscous force* (*Newton's second law*), nor *viscous dissipation* (*first law of thermodynamics*). However, no real fluid flow of engineering interest can exist without viscous forces, dissipation, and/or head losses in regions of practical importance. The engineer should always identify the flow regions where frictional effects are concentrated. When developing models for prediction, the engineer should consider the role of these viscous regions in the prediction of variables of interest and should estimate levels of error in simplified treatments of the viscous regions. In high *Reynolds number* flows, frictional regions include boundary layers, *wakes, jets, shear layers,* and flow regions surrounding *vortices.*

Froude number [274]: An order-of-magnitude estimate of the ratio of the inertial term in Newton's law of motion to the gravity force term. The Froude number is an important nondimensional group in free-surface flows, as is generally the case in channels, rivers, surface flows, etc.

fully developed [294, 325, 440]: Used by itself, the term is generally understood to imply hydrodynamically fully developed, a flow region where the velocity field is constant along a specified direction in the flow. In the fully developed region of pipe or duct flow, the velocity field is constant in the axial direction, x (i.e., it is independent of x), so that x-derivatives of velocity are zero in the fully developed region. There also exists the concept of "thermally fully developed" for the temperature field; however, unlike hydrodynamically fully developed regions where both the magnitude and shape of the velocity profile are constant in x, in thermally fully developed regions only the shape of the temperature profile is constant in x. See also *entry length.*

fundamental dimensions [15, 270]: See *dimensions.*

gage pressure [66]: *Pressure* (P) relative to atmospheric pressure (P_{atm}). That is, $P_{\text{gage}} = P - P_{\text{atm.}}$ See also *stress, pressure stress.* Thus $P_{\text{gage}} > 0$ or $P_{\text{gage}} < 0$ is simply the pressure above or below atmospheric pressure.

gas dynamics [2]: The study and analysis of gases and vapors through the macroscopic conservation laws of physics (see *fluid mechanics/dynamics*).

geometric similarity: See *similarity.*

grade lines [194]: Lines of *head* summations.

energy grade line [195]: Line describing the sum of *pressure head, velocity head,* and *elevation head.* See *head.*

hydraulic grade line [195]: Line describing the sum of *pressure head* and *elevation head.* See *head.*

Hagen–Poiseuille flow: See *Poiseuille flow.*

head [194]: A quantity (pressure, kinetic energy, etc.) expressed as an equivalent column height of a fluid. *Conservation of energy* for *steady flow* written for a *control volume* surrounding a central *streamline* with one inlet and one outlet, or shrunk to a streamline, can be written such that each term has the *dimensions* of length. Each of these terms is called a head term:

elevation head [194]: The term in the head form of *conservation of energy* (see *head*) involving distance in the direction opposite to the gravitational vector relative to a predefined datum (z).

head loss [330]: The term in the head form of *conservation of energy* (see *head*) that contains frictional losses and other irreversibilities. Without this term, the energy equation for streamlines becomes the *Bernoulli equation* in head form.

pressure head [194]: The term in the head form of *conservation of energy* (see *head*) involving pressure ($P/\rho g$).

velocity head [194]: The (*kinetic energy*) term in the head form of *conservation of energy* (see *head*) involving velocity ($V^2/2g$).

heat [41]: See *energy.*

hot-film anemometer [377]: Similar to a *hot-wire anemometer* except using a metallic film rather than a wire; used primarily for liquid flows. The measurement portion of a hot-film probe is generally larger and more rugged than that of a hot-wire probe.

hot-wire anemometer [377]: A device used to measure a velocity component locally in a gas flow based on the relationship between the flow around a thin heated wire (the hot wire), temperature of the wire, and heating of the wire resulting from a current. See also *hot-film anemometer.*

hydraulic grade line [193]: See *grade lines.*

hydraulics [1]: The *hydrodynamics* of liquid and vapor flow in pipes, ducts, and open channels. Examples include water piping systems and ventilation systems.

hydrodynamic entry length [325]: See *entry length.*

hydrodynamically fully developed [325]: See *fully developed.*

hydrodynamics [2]: The study and analysis of liquids through the macroscopic conservation laws of physics (see *fluid mechanics/dynamics*). The term is sometimes applied to *incompressible* vapor and gas flows, but when the fluid is air, the term *aerodynamics* is generally used instead.

hydrostatic pressure [189]: The component of *pressure* variation in a fluid flow that would exist in the absence of flow as a result of gravitational body force. This term appears in the hydrostatic equation and in the *Bernoulli equation.* See also *dynamic* and *static pressure.*

hypersonic [10]: An order of magnitude or more above the speed of sound (Mach number $\gg 1$).

ideal fluid: See *perfect fluid.*

ideal gas [38]: A gas at low enough density and/or high enough temperature that (a) density, pressure, and temperature are related by the ideal-gas equation of state, $P = \rho RT$, and (b) specific internal energy and enthalpy are functions only of temperature.

incompressible flow [10, 191, 406, 563]: A fluid flow where variations in density are sufficiently small to be negligible. Flows are generally incompressible either because the fluid is incompressible (liquids) or because the Mach number is low (roughly < 0.3).

induced drag [592]: See *drag force.*

inertia/inertial: The acceleration term in Newton's second law, or effects related to this term. Thus, a flow with higher inertia requires larger deceleration to be brought to rest.

inertial sublayer [340]: A highly turbulent part of a turbulent boundary layer, close to the wall but just outside the *viscous sublayer* and *buffer layer,* where *turbulent stresses* are large compared to *viscous stresses.*

intensive property [36, 150]: A fluid property that is independent of total volume or total mass (i.e., an *extensive property* per unit mass or sometimes per unit volume).

internal energy [41]: See *energy.*

inviscid (region of) flow [9, 327, 481]: Region of a fluid flow where viscous forces are sufficiently small relative to other forces (typically, pressure force) on *fluid particles* in that region of the flow to be neglected in *Newton's second law* of motion to a good level of approximation (compare with *viscous flow*). See also *frictionless flow.* An inviscid region of flow is not necessarily *irrotational.*

irrotational (region of) flow [144, 148, 325, 485, 579]: A region of a flow with negligible *vorticity* (i.e., *fluid particle* rotation). Also called *potential flow.* An irrotational region of flow is also *inviscid.*

isocontour plot: See *contour plot.*

jet: A friction-dominated region issuing from a tube or orifice and formed by surface boundary layers that have been swept behind by the mean velocity. Jets are characterized by high *shear* with the highest velocities in the center of the jet and lowest velocities at the edges. *Frictional force, viscous stress,* and *vorticity* are significant in jets.

Kármán vortex street [133]: The *two-dimensional* alternating unsteady pattern of *vortices* that is commonly observed behind circular cylinders in a flow (e.g., the vortex street behind wires in the wind is responsible for the distinct tone sometimes heard).

kinematic similarity [279]: See *similarity.*

kinematic viscosity [48]: Fluid *viscosity* divided by density.

kinematics [122]: In contrast with *dynamics,* the kinematic aspects of a fluid flow are those that do not directly involve

Newton's second law force balance. Kinematics refers to descriptions and mathematical derivations based only on conservation of mass (continuity) and definitions related to flow and deformation.

kinetic energy [41]: See *energy.*

kinetic energy correction factor [208]: *Control volume* analysis of the *conservation of energy* equation applied to tubes contains area integrals of kinetic energy flux. The integrals are often approximated as proportional to kinetic energy formed with area-averaged velocity, V_{avg}. The inaccuracy in this approximation can be significant, so a kinetic energy correction factor, α, multiplies the term to improve the approximation. The correction α depends on the shape of the *velocity profile,* is largest for *laminar* profiles (*Poiseuille flow*), and is closest to 1 in *turbulent* pipe flows at very high *Reynolds numbers.*

Lagrangian derivative [127]: See *material derivative.*

Lagrangian description [122]: In contrast with the *Eulerian description,* a Lagrangian analysis is developed from a frame of reference attached to moving material particles. For example, solid particle acceleration in the standard Newton's second law form, $\vec{F} = m\vec{a}$, is in a coordinate system that moves with the particle so that acceleration $\vec{a}$ is given by the time derivative of particle velocity. This is the typical analytical approach used for analysis of the motion of solid objects.

laminar flow [11, 323]: A stable well-ordered state of fluid flow in which all pairs of adjacent *fluid particles* move alongside one another forming laminates. A flow that is not laminar is either *turbulent* or *transitional* to turbulence, which occurs above a critical *Reynolds number.*

laser Doppler velocimetry (LDV) [378]: Also called laser Doppler anemometry (LDA). A technique for measuring a velocity component locally in a flow based on the Doppler shift associated with the passage of small particles in the flow through the small target volume formed by the crossing of two laser beams. Unlike *hot-wire* and *hot-film anemometry* and like *particle image velocimetry,* there is no interference to the flow.

lift coefficient [292, 565]: Nondimensional lift given by the lift force on a lifting object (such as an airfoil or wing) nondimensionalized by dynamic pressure of the free-stream flow times planform area of the object:

$$C_L \equiv \frac{F_L}{\frac{1}{2}\rho V^2 A}$$

Note that at high Reynolds numbers (Re >> 1), C_L is a normalized variable, whereas at Re << 1, C_L is nondimensional but is not normalized (see *normalization*). See also *drag coefficient.*

lift force [566]: The net aerodynamic force on an object perpendicular to the motion of the object.

linear strain rate [139, 140]: Synonymous with *extensional strain rate.* See *strain rate.*

losses [350]: Frictional *head losses* in pipe flows are separated into those losses in the fully developed pipe flow regions of a piping network, the *major losses,* plus head losses in other flow regions of the network, the *minor losses.* Minor loss regions include *entry lengths,* pipe couplings, bends, valves, etc. It is not unusual for minor losses to be larger than major losses.

Mach number [10]: *Nondimensional* ratio of the characteristic speed of the flow to the speed of sound. Mach number characterizes the level of *compressibility* in response to pressure variations in the flow.

major losses [347]: See *losses.*

manometer [71]: A device that measures pressure based on hydrostatic pressure principles in liquids.

material acceleration [127]: The acceleration of a *fluid particle* at the point (x, y, z) in a flow at time t. This is given by the *material derivative* of fluid velocity: $D\vec{V}(x, y, z, t)/Dt$.

material derivative [127]: Synonymous terms are *total derivative, substantial derivative,* and *particle derivative.* These terms mean the time rate of change of fluid variables (temperature, velocity, etc.) moving with a *fluid particle.* Thus, the material derivative of temperature at a point (x, y, z) at time t is the time derivative of temperature attached to a moving *fluid particle* at the point (x, y, z) in the flow at the time t. In a *Lagrangian* frame of reference (i.e., a frame attached to the moving particle), particle temperature T_{particle} depends only on time, so a time derivative is a total derivative $dT_{\text{particle}}(t)/dt$. In an Eulerian frame, the temperature *field* $T(x, y, z, t)$ depends on both position (x, y, z) and time t, so the *material derivative* must include both a partial derivative in time and a *convective derivative:* $dT_{\text{particle}}(t)/dt \equiv DT(x, y, z, t)/Dt = \partial T/\partial t + \vec{V} \cdot \vec{\nabla} T$. See also *field.*

material particle [124]: A *differential* particle, or element, that contains always the same atoms and molecules. Thus a material particle has fixed mass δm. In a fluid flow, this is the same as a *fluid particle.*

material position vector [124]: A vector $[x_{\text{particle}}(t), y_{\text{particle}}(t), z_{\text{particle}}(t)]$ that defines the location of a *material particle* as a function of time. Thus the material position vector in a fluid flow defines the trajectory of a *fluid particle* in time.

mean: Synonymous with *average.*

mechanical energy [180, 207]: See *energy.*

mechanics [2]: The study and analysis of matter through the macroscopic conservation laws of physics (mass, momentum, energy, second law).

minor losses [347]: See *losses.*

mixing length [337]: See *turbulence models.*

momentum: The momentum of a *material particle* (or *fluid particle*) is the mass of the material particle times its velocity.

The momentum of a macroscopic volume of material particles is the integrated momentum per unit volume over the volume, where momentum per unit volume is the density of the material particle times its velocity. Note that momentum is a vector.

momentum flux correction factor [236]: A correction factor added to correct for approximations made in the simplification of the area integrals for the momentum flux terms in the control volume form of *conservation of momentum.*

Moody chart [341]: A commonly used plot of the *friction factor* as a function of the Reynolds number and roughness parameter for fully developed pipe flow. The chart is a combination of flow theory for laminar flow with a graphical representation of an empirical formula by Colebrook to a large set of experimental data for turbulent pipe flow of various values of "sandpaper" roughness.

natural flow [11]: Contrast with *forced flow.*

Navier–Stokes equation [429, 474]: *Newton's second law* of fluid motion (or *conservation of momentum*) written for a fluid particle (the *differential* form) with the *viscous stress tensor* replaced by the *constitutive relationship* between *stress* and *strain rate* for Newtonian fluids. Thus the Navier–Stokes equation is simply Newton's law written for Newtonian fluids.

Newtonian fluid [47, 427]: When a fluid is subjected to a *shear stress,* the fluid continuously changes shape (deformation). If the fluid is Newtonian, the rate of deformation (i.e., strain rate) is proportional to the applied shear stress and the constant of proportionality is called *viscosity.* In general flows, the rate of deformation of a *fluid particle* is described mathematically by a *strain rate* tensor and the *stress* by a *stress tensor.* In flows of Newtonian fluids, the stress tensor is proportional to the strain rate tensor, and the constant of proportionality is called *viscosity.* Most common fluids (water, oil, gasoline, air, most gases and vapors) without particles or large molecules in suspension are Newtonian.

Newton's second law [230]: See *conservation of momentum.*

nondimensionalization [272]: The process of making a dimensional variable dimensionless by dividing the variable by a *scaling parameter* (a single variable or a combination of variables) that has the same dimensions. For example, the surface pressure on a moving ball might be nondimensionalized by dividing it by ρV^2, where ρ is fluid density and V is free-stream velocity. See also *normalization.*

non-Newtonian fluid [427]: A non-Newtonian fluid is one that deforms at a rate that is not linearly proportional to the stress causing the deformation. Depending on the manner in which *viscosity* varies with *strain rate,* non-Newtonian fluids can be labeled shear thinning (viscosity decreases with increasing strain rate), shear thickening (viscosity increases with increasing strain rate), and viscoelastic (when the shearing forces the fluid particles to return partially to an earlier shape). Suspensions and liquids with long-chain molecules are generally non-Newtonian. See also *Newtonian fluid* and *viscosity.*

normal stress [3, 231]: See *stress.*

normalization [272]: A particular *nondimensionalization* where the *scaling parameter* is chosen so that the nondimensionalized variable attains a maximum value that is of order 1 (say, within roughly 0.5 to 2). Normalization is more restrictive (and more difficult to do properly) than nondimensionalization. For example, $P/(\rho V^2)$ discussed under *nondimensionalization* is also normalized pressure on a flying baseball (where Reynolds number $\text{Re} \gg 1$), but is simply nondimensionalization of surface pressure on a small glass bead dropping slowly through honey (where $\text{Re} \ll 1$).

no-slip condition [6, 438]: The requirement that at the interface between a fluid and a solid surface, the fluid velocity and surface velocity are equal. Thus if the surface is fixed, the fluid must obey the *boundary condition* that fluid velocity = 0 at the surface.

one-dimensional [12]: See *dimensionality.*

open system [14, 149]: Same as *control volume.*

particle derivative [127, 129]: See *material derivative.*

particle image velocimetry (PIV) [131, 380]: A technique for measuring a velocity component locally in a flow based on tracking the movement of small particles in the flow over a short time using pulsed lasers. Unlike *hot-wire* and *hot-film anemometry* and like laser Doppler velocimetry, there is no interference to the flow.

pathline [130, 182]: A curve mapping the trajectory of a *fluid particle* as it travels through a flow over a period of time. Mathematically, this is the curve through the points mapped out by the *material position vector* $[x_{\text{particle}}(t), y_{\text{particle}}(t), z_{\text{particle}}(t)]$ over a defined period of time. Thus, pathlines are formed over time, and each fluid particle has its own pathline. In a steady flow, fluid particles move along streamlines, so pathlines and streamlines coincide. In a nonsteady flow, however, pathlines and streamlines are generally very different. Contrast with *streamline.*

perfect fluid: Also called an *ideal fluid,* the concept of a fictitious fluid that can flow in the absence of all frictional effects. There is no such thing as a perfect fluid, even as an approximation, so the engineer need not consider the concept further.

periodic: An unsteady flow in which the flow oscillates about a steady mean.

Pitot-static probe [190, 365]: A device used to measure fluid velocity through the application of the Bernoulli equation with simultaneous measurement of *static* and *stagnation pressures.* Also called a Pitot-Darcy probe.

planar flow [419, 490]: A *two-dimensional* flow with two nonzero components of velocity in Cartesian coordinates that vary only in the two coordinate directions of the flow. Thus, all partial derivatives perpendicular to the plane of the flow are zero. See also *axisymmetric flow* and *dimensionality.*

Poiseuille flow [316, 332]: *Fully developed laminar flow* in a pipe or duct. Also called *Hagen–Poiseuille flow.* The mathematical model relationships for Pouiseuille flow relating the flow rate and/or velocity profile to the pressure drop along the pipe/duct, fluid viscosity and geometry are sometimes referred to as *Poiseuille's law* (although strictly not a "law" of mechanics). The velocity profile of all Poiseuille flows is parabolic, and the rate of axial pressure drop is constant.

Poiseuille's law [330]: See *Poiseuille flow.*

potential energy [41]: See *energy.*

potential flow [485]: Synonymous with *irrotational flow.* This is a region of a flow with negligible *vorticity* (i.e., *fluid particle* rotation). In such regions, a velocity *potential function* exists (thus the name).

potential function [485]: If a region of a flow has zero *vorticity* (*fluid particle* spin), the velocity vector in that region can be written as the gradient of a scalar function called the velocity potential function, or simply the potential function. In practice, potential functions are often used to model flow regions where vorticity levels are small but not necessarily zero.

power [202]: *Work* per unit time; time rate at which work is done.

pressure [3, 66]: See *stress.*

pressure force: As applicable to Newton's second law, this is the force acting on a *fluid particle* that arises from spatial gradients in pressure within the flow. See also *stress, pressure stress.*

pressure work: See *flow work.*

primary dimension [15, 270]: See *dimensions.*

profile plot [137]: A graphical representation of the spatial variation of a fluid property (temperature, pressure, strain rate, etc.) through a region of a fluid flow. A profile plot defines property variations in part of a *field* (e.g., a temperature profile might define the variation of temperature along a line within the temperature field).

> **velocity profile** [139]: The spatial variation in a velocity component or vector through a region of a fluid flow. For example, in a pipe flow the velocity profile generally defines the variation in axial velocity with radius across the pipe cross section, while a *boundary layer* velocity profile generally defines variation in axial velocity normal to the surface. The velocity profile is part of a velocity *field.*

quasi-steady flow [475]: See *steady flow.*

Reynolds number [11, 279, 324]: An order-of-magnitude estimate of the ratio of the following two terms in Newton's second law of motion over a region of the flow: the *inertial* (or acceleration) term over the viscous force term. Most but not all Reynolds numbers can be written as an appropriate characteristic velocity V times a characteristic length scale L consistent with the velocity V, divided by the kinematic viscosity ν of the fluid: $\mathrm{Re} = VL/\nu$. The Reynolds number is arguably the most important nondimensional *similarity* parameter in fluid flow analysis since it gives a rough estimate of the importance of frictional force in the overall flow.

Reynolds stress [337]: Velocity components (and other variables) in turbulent flows are separated into mean plus fluctuating components. When the equation for mean streamwise velocity component is derived from the *Navier–Stokes equation,* six new terms appear given by fluid density times the averaged product of two velocity components. Because these terms have the same units as *stress* (force/area), they are called turbulent stresses or Reynolds stresses (in memory of Osborne Reynolds who first quantified turbulent variables as mean + fluctuation). Just as *viscous stresses* can be written as a tensor (or matrix), we define a Reynolds stress tensor with Reynolds normal stress components and Reynolds shear stress components. Although Reynolds stresses are not true stresses, they have qualitatively similar effects as do viscous stresses, but as a result of the large chaotic *vortical* motions of turbulence rather than the microscopic molecular motions that underlie viscous stresses.

Reynolds transport theorem [149]: The mathematical relationship between the time rate of change of a fluid property in a *system* (volume of fixed mass moving with the flow) and the time rate of change of a fluid property in a *control volume* (volume, usually fixed in space, with fluid mass moving across its surface). This finite volume expression is closely related to the *material (time) derivative* of a fluid property attached to a moving *fluid particle.* See also *conservation laws.*

rheology [427]: The study and mathematical representation of the deformation of different fluids in response to surface forces, or *stress.* The mathematical relationships between stress and deformation rate (or strain rate) are called *constitutive equations.* The Newtonian relationship between *stress* and *strain rate* is the simplest example of a rheological constitutive equation. See also *Newtonian* and *non-Newtonian fluid.*

rotation rate [139]: The angular velocity, or rate of spin, of a *fluid particle* (a vector, with units rad/s, given by 1/2 the curl of the velocity vector). See also *vorticity.*

rotational flow [144, 146]: Synonymous with v*ortical flow,* this term describes a flow field, or a region of a flow field, with significant levels of *vorticity.*

saturation pressure [39]: The pressure at which the phase of a simple compressible substance changes between liquid and vapor at fixed temperature.

saturation temperature [39]: The temperature at which the phase of a simple compressible substance changes between liquid and vapor at fixed pressure.

scaling parameter [273]: A single variable, or a combination of variables, that is chosen to nondimensionalize a variable of interest. See also *nondimensionalization* and *normalization.*

schlieren technique [135]: An experimental technique to visualize flows based on the refraction of light from varying fluid density. The illuminance level in a schlieren image responds to the first spatial derivative of density.

secondary dimensions [15]: See *dimensions.*

shadowgraph technique [135]: An experimental technique to visualize flows based on the refraction of light from varying fluid density. The illuminance level in a shadowgraph image responds to the second spatial derivative of density.

shear: Refers to gradients (derivatives) in velocity components in directions normal to the velocity component.

shear force: See *stress, shear stress.*

shear layer [147]: A quasi two-dimensional flow region with a high gradient in streamwise velocity component in the transverse flow direction. Shear layers are inherently *viscous* and *vortical* in nature.

shear rate: The gradient in streamwise velocity in the direction perpendicular to the velocity. Thus, if streamwise (x) velocity u varies in y, the shear rate is du/dy. The term is applied to *shear flows,* where shear rate is twice the *shear strain rate.* See also *strain rate.*

shear strain [139, 141]: See *strain rate.*

shear stress [3, 231]: See *stress, shear stress.*

shear thickening fluid [428]: See *non-Newtonian fluid.*

shear thinning fluid [428]: See *non-Newtonian fluid.*

SI system [15]: See *units.*

similarity [277, 522]: The principle that allows one to quantitatively relate one flow to another when certain conditions are met. *Geometric similarity,* for example, must be true before one can hope for *kinematic* or *dynamic similarity.* The quantitative relationship that relates one flow to another is developed using a combination of dimensional analysis and data (generally, experimental, but also numerical or theoretical).

dynamic similarity [278]: If two objects are *geometrically* and *kinematically similar,* then if the ratios of all forces (pressure, viscous stress, gravity force, etc.) between a point in the flow surrounding one object, and the same point scaled appropriately in the flow surrounding the other object, are all the same at all corresponding pairs of points, the flow is *dynamically similar.*

geometric similarity [277]: Two objects of different size are geometrically similar if they have the same geometrical shape (i.e., if all dimensions of one are a constant multiple of the corresponding dimensions of the other).

kinematic similarity [277]: If two objects are *geometrically similar,* then if the ratios of all velocity components between a point in the flow surrounding one object, and the same point scaled appropriately in the flow surrounding the other object, are all the same at all corresponding pairs of points, the flow is *kinematically similar.*

skin friction [523, 570]: Surface shear stress τ_w nondimensionalized by an appropriate *dynamic pressure* $\frac{1}{2}\rho V^2$. Also called the skin friction coefficient, C_f.

solid: A material that when sheared either deforms to a fixed static position (after which deformation stops) or fractures. See also *fluid.*

sonic [10]: At the speed of sound (*Mach number* = 1).

specific gravity [37]: Fluid density nondimensionalized by the density of liquid water at 4°C and atmospheric pressure (1 g/cm^3 or 1000 kg/m^3). Thus, specific gravity, $\text{SG} = \rho/\rho_{\text{water}}$.

specific weight [17, 237]: The weight of a fluid per unit volume, i.e., fluid density times acceleration due to gravity (specific weight, $\gamma \equiv \rho g$).

spin: See *rotation rate* and *vorticity.*

stability [93]: A general term that refers to the tendency of a material particle or object (fluid or solid) to move away from or return when displaced slightly from its original position.

neutrally stable [92]: See *stability.* When displaced slightly, the particle or object will remain in its displaced position.

stable [92]: See *stability.* When displaced slightly, the particle or object will return to its original position.

unstable [93]: See *stability.* When displaced slightly, the particle or object will continue to move from its original position.

stagnation point [190]: A point in a fluid flow where the velocity goes to zero. For example, the point on the *streamline* that intersects the nose of a moving projectile is a stagnation point.

stall [535, 570]: The phenomenon of massive *flow separation* from the surface of a wing when *angle of attack* exceeds a critical value, and consequent dramatic loss of lift and increase in drag. A plane in stall drops rapidly and must have its nose brought down to reestablish attached boundary layer flow and regenerate lift and reduce drag.

static pressure [189]: Another term for *pressure,* used in context with the *Bernoulli equation* to distinguish it from *dynamic pressure.*

statics [2]: The mechanical study and analysis of material that is fully at rest in a specific frame of reference.

steady flow [11, 190]: A flow in which all fluid variables (velocity, pressure, density, temperature, etc.) at all fixed points in the flow are constant in time (but generally vary from place to place). Thus, in steady flows all partial derivatives in time are zero. Flows that are not precisely steady but that change sufficiently slowly in time to neglect time derivative terms with relatively little error are called *quasi-steady.*

Stokes flow [478]: See *creeping flow.*

strain [141]: See *strain rate.*

strain rate [139]: Strain rate can also be called *deformation rate.* This is the rate at which a *fluid particle* deforms (i.e., changes shape) at a given position and time in a fluid flow. To fully quantify all possible changes in shape of a *three-dimensional* fluid particle require six numbers. Mathematically, these are the six independent components of a second-rank symmetric strain rate tensor, generally written as a symmetric 3 × 3 matrix. Strain is time-integrated strain rate and describes deformation of a fluid particle after a period of time. See *stress.*

> **extensional strain rate** [139]: The components of strain rate that describe elongation or compression of a *fluid particle* in one of the three coordinate directions. These are the three diagonal elements of the strain rate tensor. The definition of extensional strain depends on one's choice of coordinate axes. Also called *linear strain rate.*
>
> **shear strain rate** [139, 141]: The components of strain rate that describe deformation of a *fluid particle* in response to shear changing an angle between planes mutually perpendicular to the three coordinate axes. These are the off-diagonal elements of the strain rate tensor. The definition of shear strain depends on one's choice of coordinate axes.
>
> **volumetric strain rate** [141]: Rate of change of volume of a *fluid particle* per unit volume. Also called bulk strain rate and rate of volumetric dilatation.

streakline [132]: Used in flow visualization of fluid flows, this is a curve defined over time by the release of a marker (dye or smoke) from a fixed point in the flow. Contrast with *pathline* and *streamline.* In a steady flow, streamlines, *pathlines,* and *streaklines* all coincide. In a nonsteady flow, however, these sets of curves are each different from one another.

stream function [309, 412]: The two velocity components in a *two-dimensional* steady incompressible flow can be defined in terms of a single two-dimensional function ψ that automatically satisfies conservation of mass (the continuity equation), reducing the solution of the two-component velocity field to the solution of this single stream function. This is done by writing the two velocity components as spatial derivatives of the stream function. A wonderful property of the stream function is that *(iso)contours* of constant ψ define *streamlines* in the flow.

streamline [129, 413, 493, 565]: A curve that is everywhere tangent to a velocity vector in a fluid velocity *field* at a fixed instant in time. Thus, the streamlines indicate the direction of the fluid motions at each point. In a *steady flow,* streamlines are constant in time and *fluid particles* move along streamlines. In a *nonsteady flow* the streamlines change with time and fluid particles do not move along streamlines. Contrast with *pathline.*

streamtube [130]: A bundle of streamlines. A streamtube is usually envisioned as a surface formed by an infinite number of streamlines initiated within the flow on a circular circuit and tending to form a tubelike surface in some region of the flow.

stress [3]: A component of a force distributed over an area is written as the integral of a stress over that area. Thus, stress is the force component dF_i on a differential area element divided by the area of the element dA_j (in the limit $dA_j \to 0$), where i and j indicate a coordinate direction x, y, or z. Stress $\sigma_{ij} = dF_i/dA_j$ is therefore a force component per unit area in the i-direction on surface j. To obtain the surface force from stress, one integrates stress over the corresponding surface area. Mathematically, there are six independent components of a second-rank symmetric *stress tensor,* generally written as a symmetric 3 × 3 matrix.

> **normal stress** [3, 233]: A stress (force component per unit area) that acts perpendicular to the area. Therefore σ_{xx}, σ_{yy}, and σ_{zz} are normal stresses. The normal force over a surface is the net force from shear stress, given by integrating the shear stress over the surface area. The normal stresses are the diagonal elements of the *stress tensor.*
>
> **pressure stress** [3]: In a fluid at rest all stresses are normal stresses and all stresses act inward on a surface. At a fixed point, the three normal stresses are equal and the magnitude of these equal normal stresses is called pressure. Thus, in a static fluid $\sigma_{xx} = \sigma_{yy} = \sigma_{zz} = -P$, where P is pressure. In a moving fluid, stresses in addition to pressure are *viscous stresses.* A pressure force on a surface is the pressure stress integrated over the surface. The pressure force per unit volume on a *fluid particle* for Newton's second law, however, is the negative of the gradient (spatial derivatives) of pressure at that point.
>
> **Reynolds stress** [339]: See *Reynolds stress.*
>
> **shear stress** [3, 233]: A stress (force component per unit area) that acts tangent to the area. Therefore, σ_{xy}, σ_{yx}, σ_{xz}, σ_{zx}, σ_{yz}, and σ_{zy} are shear stresses. The shear force over a surface is the net force from shear stress, given by integrating the shear stress over the surface area. The shear stresses are the off-diagonal elements of the *stress tensor.*
>
> **turbulent stress** [336, 337]: See *Reynolds stress.*
>
> **viscous stress** [429]: Flow creates stresses in the fluid that are in addition to hydrostatic pressure stresses. These

additional stresses are viscous since they arise from friction-induced fluid deformations within the flow. For example, $\sigma_{xx} = -P + \tau_{xx}$, $\sigma_{yy} = -P + \tau_{yy}$, and $\sigma_{zz} = -P + \tau_{zz}$, where τ_{xx}, τ_{yy}, and τ_{zz} are viscous normal stresses. All shear stresses result from friction in a flow and are therefore viscous stresses. A viscous force on a surface is a viscous stress integrated over the surface. The viscous force per unit volume on a *fluid particle* for Newton's second law, however, is the divergence (spatial derivatives) of the viscous stress tensor at that point.

stress tensor [233, 421]: See *stress.*

subsonic [10]: Below the speed of sound (*Mach number* < 1).

substantial derivative [127]: See *material derivative.*

supersonic [10]: Above the speed of sound (*Mach number* > 1).

surface tension [51]: The force per unit length at a liquid–vapor or liquid–liquid interface resulting from the imbalance in attractive forces among like liquid molecules at the interface.

system [14, 148]: Usually when the word *system* is used by itself, *closed system* is implied, in contrast with a *control volume* or *open system.*

closed system [14]: A volume specified for analysis that encloses always the same *fluid particles.* Therefore, no flow crosses any part of the volume's surface and a closed system must move with the flow. Note that Newton's law analysis of solid particles is generally a *closed system* analysis, sometimes referred to as a free body.

open system [14]: A volume specified for analysis where flow crosses at least part of the volume's surface. Also called a *control volume.*

thermal energy [41]: See *energy.*

three-dimensional [563]: See *dimensionality.*

timeline [134]: Used for visualization of fluid flows, this is a curve defined at some instant in time by the release of a marker from a line in the flow at some earlier instant in time. The timeline, often used to approximate a *velocity profile* in a laboratory flow, is very different from *streaklines, pathlines,* and *streamlines.*

tip vortex [592]: *Vortex* formed off each tip of an airplane wing as a byproduct of lift. Synonymous with *trailing vortex.* See also *induced drag.*

total derivative [125, 127, 129]: See *material derivative.*

total energy [41]: See *energy.*

trailing vortex [595]: See *tip vortex.*

trajectory: See *pathline.*

transient period: A time-dependent period of flow evolution leading to a new equilibrium period that is generally, but not necessarily, steady. An example is the start-up period after a jet engine is switched on, leading to a steady (equilibrium) jet flow.

transitional flow [11, 323]: An unstable *vortical* fluid flow at a Reynolds number higher than a critical value that is large relative to 1, but is not sufficiently high that the flow has reached a fully *turbulent flow* state. Transitional flows often oscillate randomly between *laminar* and turbulent states.

turbulence models [337]: Constitutive model relationships between *Reynolds stresses* and the mean velocity field in turbulent flows. Such model equations are necessary to solve the equation for mean velocity. A simple and widely used modeled form for the Reynolds stresses is to write them like the Newtonian relationship for viscous stresses, as proportional to the mean strain rate, with the proportionality being a *turbulent viscosity* or *eddy viscosity.* However, unlike Newtonian fluids, the eddy viscosity is a strong function of the flow itself, and the different ways in which eddy viscosity is modeled as a function of other calculated flow field variables constitute different eddy viscosity models. One traditional approach to modeling eddy viscosity is in terms of a *mixing length,* which is made proportional to a length set by the flow.

turbulent flow [11, 323]: An unstable disordered state of *vortical* fluid flow that is inherently *unsteady* and that contains eddying motions over a wide range of sizes (or scales). Turbulent flows are always at *Reynolds numbers* above a critical value that is large relative to 1. Mixing is hugely enhanced, surface shear stresses are much higher, and head loss is greatly increased in turbulent flows as compared to corresponding *laminar flows.*

turbulent stress [336, 337]: See *Reynolds stress.*

turbulent viscosity [337]: See *turbulence models.*

two-dimensional [562]: See *dimensionality.*

units [15, 270]: A specific system to quantify numerically the dimensions of a physical quantity. The most common systems of units are SI (kg, N, m, s), English (lbm, lbf, ft, s), BGS (slug, lb, ft, s), and cgs (g, dyne, cm, s). See also *dimensions.*

unsteady flow [11]: A flow in which at least one variable at a fixed point in the flow changes with time. Thus, in unsteady flows a partial derivative in time is nonzero for at least one point in the flow.

vapor pressure [39]: The pressure below which a fluid, at a given temperature, will exist in the vapor state. See also *cavitation* and *saturation pressure.*

velocity: A vector that quantifies the rate of change in position and the direction of motion of a material particle.

velocity field [122]: See *field.*

velocity profile [139]: See *profile plots.*

viscoelastic fluid [427]: See *non-Newtonian fluid.*

viscosity [46, 580]: See *Newtonian fluid.* Viscosity is a property of a fluid that quantifies the ratio of shear stress to rate of deformation (strain rate) of a *fluid particle.* (Therefore viscosity has the dimensions of stress/strain rate, or $Ft/L^2 = m/Lt$.) Qualitatively, viscosity quantifies the level by which a particular fluid resists deformation when subjected to shear stress (frictional resistance or *friction*). Viscosity is a measured property of a fluid and is a function of temperature. For Newtonian fluids, viscosity is independent of the rate of applied stress and strain rate. The viscous nature of *non-Newtonian fluids* is more difficult to quantify in part because viscosity varies with strain rate. The terms *absolute viscosity, dynamic viscosity,* and *viscosity* are synonymous. See also *kinematic viscosity.*

viscous (regions of) flow [9]: Regions of a fluid flow where *viscous force*s are significant relative to other forces (typically, pressure force) on *fluid particles* in that region of the flow, and therefore cannot be neglected in *Newton's second law* of motion (compare with *inviscid flow*).

viscous (or frictional) force: As applicable to Newton's second law, this is the force acting on a *fluid particle* that arises from spatial gradients in viscous (or frictional) stresses within the flow. The viscous force on a surface is the viscous stress integrated over the surface. See also *stress, viscous stress.*

viscous stress tensor [427]: See *stress.* Also called the *deviatoric stress tensor.*

viscous sublayer [340, 534, 580]: The part of a turbulent boundary layer adjacent to the surface that contains the highest *viscous stresses.* The velocity gradient in this layer adjacent to the wall is exceptionally high. See also *inertial layer* and *buffer layer.*

vortex: A local structure in a fluid flow characterized by a concentration of vorticity (i.e., *fluid particle* spin or rotation) in a tubular core with circular streamlines around the core axis. A tornado, hurricane, and bathtub vortex are common examples of vortices. Turbulent flow is filled with small vortices of various sizes, strengths, and orientations.

vortical flow: Synonymous with *rotational flow,* this term describes a flow field, or a region of a flow field, with significant levels of *vorticity.*

vorticity [144]: Twice the angular velocity, or rate of spin, of a *fluid particle* (a vector, with units rad/s, given by the curl of the velocity vector). See also *rotation rate.*

wake [570]: The friction-dominated region behind a body formed by surface boundary layers that are swept to the rear by the free-stream velocity. Wakes are characterized by high *shear* with the lowest velocities in the center of the wake and highest velocities at the edges. *Frictional force, viscous stress,* and *vorticity* are significant in wakes.

work [202]: See *energy.*