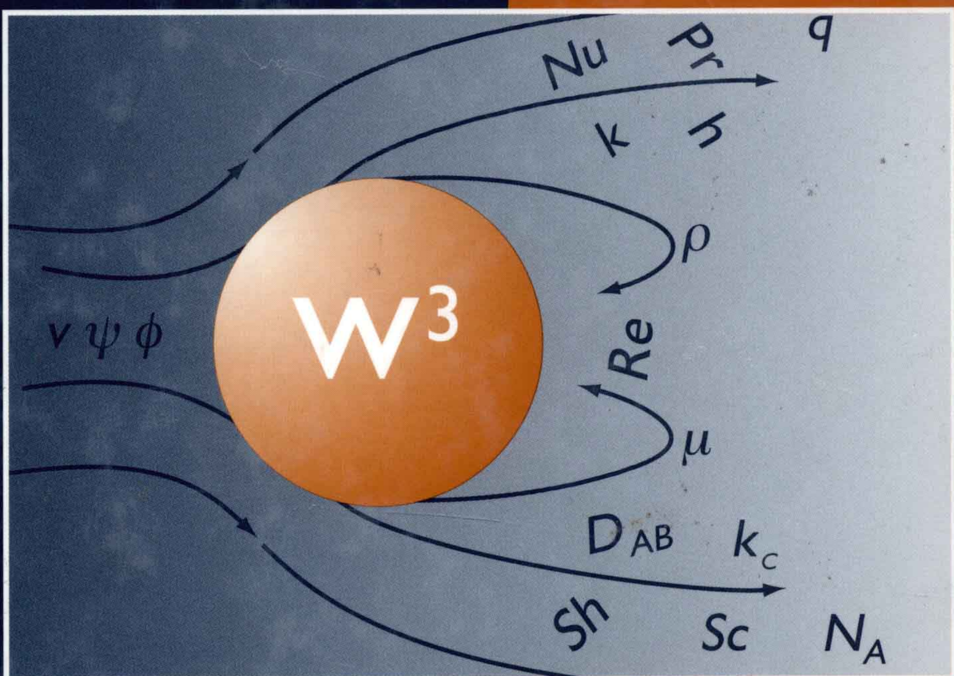
Fundamentals of Momentum, Heat, and Mass Transfer

4th Edition



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Fourth Edition

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Preface to the 4th Edition

The first edition of *Fundamentals of Momentum, Heat, and Mass Transfer*, published in 1969, was written to become a part of what was then known as the "engineering science core" of most engineering curricula. Indeed, requirements for ABET accreditation have stipulated that a significant part of all curricula must be devoted to fundamental subjects. The emphasis on engineering science has continued over the intervening years, but the degree of emphasis has diminished as new subjects and technologies have entered the world of engineering education. Nonetheless, the subjects of momentum transfer (fluid mechanics), heat transfer, and mass transfer remain, at least in part, important components of all engineering curricula. It is in this context that we now present the fourth edition.

Advances in computing capability have been astonishing since 1969. At that time, the pocket calculator was quite new and not generally in the hands of engineering students. Subsequent editions of this book included increasingly sophisticated solution techniques as technology advanced. Now, more than 30 years since the first edition, computer competency among students is a fait accompli and many homework assignments are completed using computer software that takes care of most mathematical complexity, and a good deal of physical insight. We do not judge the appropriateness of such approaches, but they surely occur and will do so more frequently as software becomes more readily available, more sophisticated, and easier to use.

In this edition, we still include some examples and problems that are posed in English units, but a large portion of the quantitative work presented is now in SI units. This is consistent with most of the current generation of engineering textbooks. There are still some subdisciplines in the thermal/fluid sciences that use English units conventionally, so it remains necessary for students to have some familiarity with pounds, mass, slugs, feet, psi, and so forth. Perhaps a fifth edition, if it materializes, will finally be entirely SI.

We, the original three authors (W^3), welcome Dr. Greg Rorrer to our team. Greg is a member of the faculty of the Chemical Engineering Department at Oregon State University with expertise in biochemical engineering. He has had a significant influence on this edition's sections on mass transfer, both in the text and in the problem sets at the end of Chapters 24 through 31. This edition is unquestionably strengthened by his contributions, and we anticipate his continued presence on our writing team.

We are gratified that the use of this book has continued at a significant level since the first edition appeared some 30 years ago. It is our continuing belief that the transport phenomena remain essential parts of the foundation of engineering education and practice. With the modifications and modernization of this fourth edition, it is our hope that *Fundamentals of Momentum, Heat, and Mass Transfer* will continue to be an essential part of students' educational experiences.

Corvallis, Oregon
March 2000

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Contents

Chapter 1

Concepts and Definitions

Momentum transfer in a fluid involves the study of the motion of fluids and the forces that produce these motions. From Newton's second law of motion it is known that force is directly related to the time rate of change of momentum of a system. Excluding action-at-a-distance forces such as gravity, the forces acting on a fluid, such as those resulting from pressure and shear stress, may be shown to be the result of microscopic (molecular) transfer of momentum. Thus the subject under consideration which is historically fluid mechanics may equally be termed momentum transfer.

The history of fluid mechanics shows the skillful blending of the nineteenth- and twentieth century analytical work in hydrodynamics with the empirical knowledge in hydraulics that man has collected over the ages. The mating of these separately developed disciplines was started by Ludwig Prandtl in 1904 with his boundary-layer theory, which was verified by experiment. Modern fluid mechanics, or momentum transfer, is both analytical and experimental.

Each area of study has its phraseology and nomenclature. Momentum transfer being typical, the basic definitions and concepts will be introduced in order to provide a basis for communication.

1.1 FLUIDS AND THE CONTINUUM

A fluid is defined as a substance which deforms continuously under the action of a shear stress. An important consequence of this definition is that when a fluid is at rest, there can be no shear stresses. Both liquids and gases are fluids. Some substances such as glass are technically classified as fluids. However, the rate of deformation in glass at normal temperatures is so small as to make its consideration as a fluid impractical.

Concept of a Continuum. Fluids, like all matter, are composed of molecules whose numbers stagger the imagination. In a cubic inch of air at room conditions there are some 10^{20} molecules. Any theory which would predict the individual motions of this many molecules would be extremely complex, far beyond our present abilities. While both the kinetic theory of gases and statistical mechanics treat the motions of molecules, this is done in terms of statistical groups rather than in terms of individual molecules.

Most engineering work is concerned with the macroscopic or bulk behavior of a fluid rather than with the microscopic or molecular behavior. In most cases it is convenient to think of a fluid as a continuous distribution of matter or a *continuum*. There are, of course, certain instances in which the concept of a continuum is not valid. Consider, for example, the number of molecules in a small volume of a gas at rest. If the volume were taken small enough, the number of molecules per unit volume would be time-dependent for the microscopic volume even though the macroscopic volume had a constant number of molecules in it. The concept of a continuum would be valid only for the latter case. The validity of the continuum approach is seen to be dependent upon the type of information desired rather than the nature of the fluid. The treatment of fluids as continua is valid whenever the smallest fluid volume of interest contains a sufficient number of molecules to make statistical averages meaningful. The macroscopic properties of a continuum are considered to vary smoothly (continuously) from point to point in the fluid. Our immediate task is to define these properties at a point.

1.2 PROPERTIES AT A POINT

When a fluid is in motion the quantities associated with the state and the motion of the fluid will vary from point to point. The definition of some fluid variables at a point is presented below.

Density at a Point. The density of a fluid is defined as the mass per unit volume. Under flow conditions, particularly in gases, the density may vary greatly throughout the fluid. The density, ρ, at a particular point in the fluid is defined as

$$\rho = \lim_{\Delta V \to \delta V} \frac{\Delta m}{\Delta V}$$

where Δm is the mass contained in a volume ΔV, and δV is the smallest volume surrounding the point for which statistical averages are meaningful. The limit is shown in Figure 1.1.

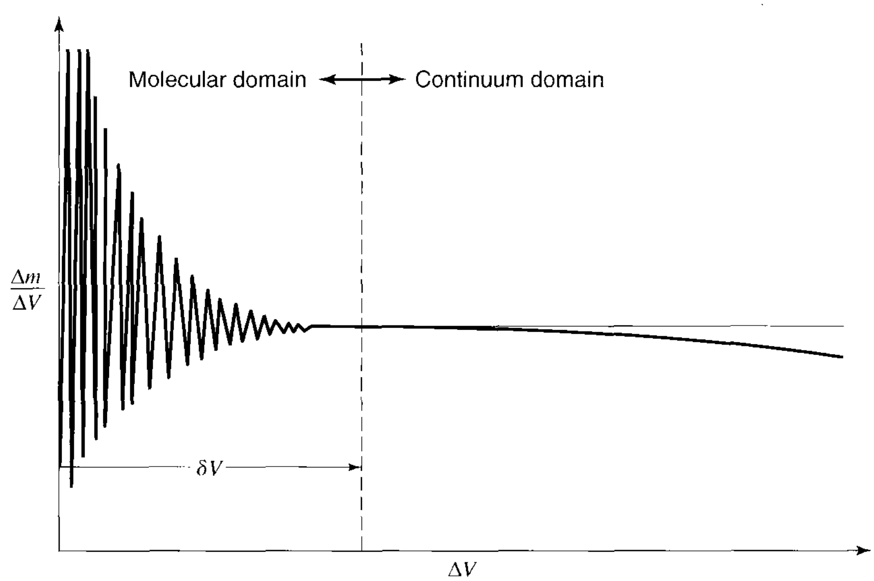

Figure 1.1 Density at a point.

The concept of the density at a mathematical point, that is, at $\Delta V = 0$ is seen to be fictitious; however, taking $\rho = \lim_{\Delta V \to 0} (\Delta m/\Delta V)$ is extremely useful, as it allows us to describe fluid flow in terms of continuous functions. The density, in general, may vary from point to point in a fluid and may also vary with respect to time as in a punctured automobile tire.

Fluid Properties and Flow Properties. Some fluids, particularly liquids, have densities which remain almost constant over wide ranges of pressure and temperature. Fluids which exhibit this quality are usually treated as being incompressible. The effects of compressibility, however, are more a property of the situation than of the fluid itself. For example, the flow of air at low velocities is described by exactly the same equations that describe the flow of water. From a static viewpoint air is a compressible fluid and water incompressible. Instead of being classified according to the fluid, compressibility effects are considered a property of the flow. A distinction, often subtle, is made between the properties of the fluid and the properties of the flow, and the student is hereby alerted to the importance of this concept.

Stress at a Point. Consider the force $\mathbf{\Delta F}$ acting on an element ΔA of the body shown in Figure 1.2. The force $\mathbf{\Delta F}$ is resolved into components normal and parallel to the surface of the element. The force per unit area or stress at a point is defined as the limit of $\mathbf{\Delta F}/\Delta A$ as $\Delta A \to \delta A$, where δA is the smallest area for which statistical averages are meaningful

$$\lim_{\Delta A \to \delta A} \frac{\Delta F_n}{\Delta A} = \sigma_{ii} \qquad \lim_{\Delta A \to \delta A} \frac{\Delta F_s}{\Delta A} = \tau_{ij}$$

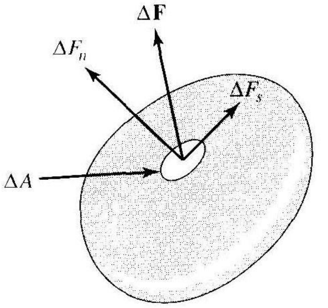

Figure 1.2 Force on an element of fluid.

Here σ_{ii} is called the normal stress and τ_{ij} the shear stress. In this text the double-subscript stress notation as used in solid mechanics will be employed. The student will recall that normal stress is positive in tension. The limiting process for the normal stress is illustrated in Figure 1.3.

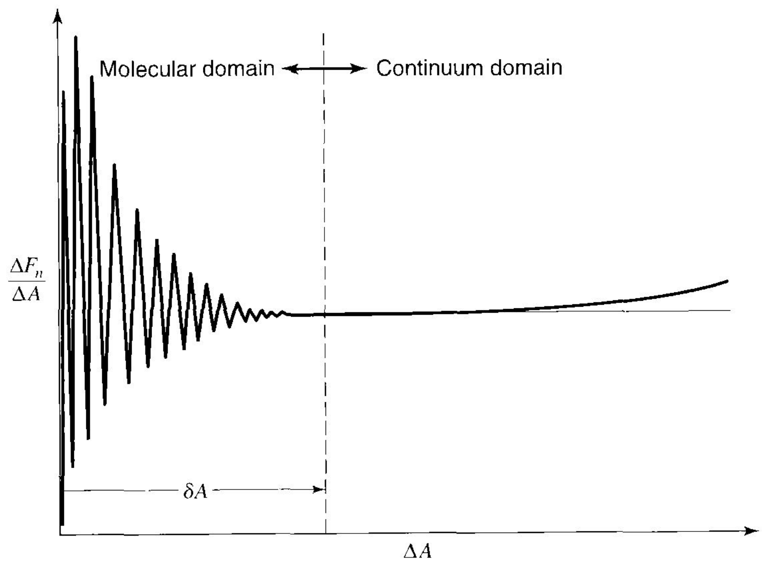

Figure 1.3 Normal stress at a point.

Forces acting on a fluid are divided into two general groups: body forces and surface forces. Body forces are those which act without physical contact, for example, gravity and electrostatic forces. On the other hand, pressure and frictional forces require physical contact for transmission. Since a surface is required for the action of these forces they are called surface forces. Stress is therefore a surface force per unit area.*

Pressure at a Point in a Static Fluid. For a static fluid, the normal stress at a point may be determined from the application of Newton's laws to a fluid element as the fluid element approaches zero size. It may be recalled that there can be no shearing stress in a static fluid. Thus the only surface forces present will be those due to normal stresses. Consider the element shown in Figure 1.4. This element, while at rest, is acted upon by gravity and normal stresses. The weight of the fluid element is $\rho \mathbf{g}(\Delta x\, \Delta y\, \Delta z/2)$.

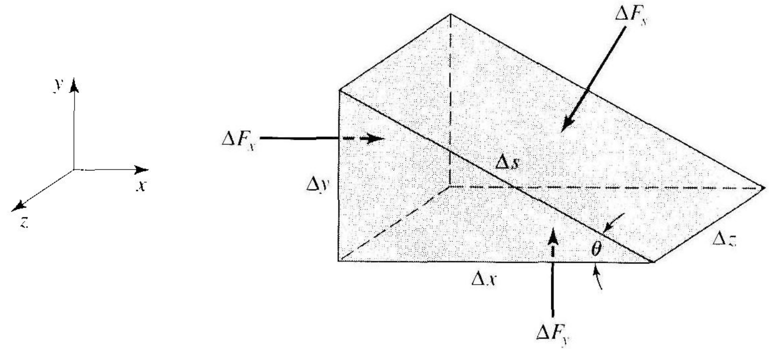

Figure 1.4 Element in a static fluid.

For a body at rest, $\Sigma \mathbf{F} = 0$. In the x direction

$$\Delta F_x - \Delta F_s \sin\theta = 0$$

Since $\sin\theta = \Delta y/\Delta s$, the above equation becomes

$$\Delta F_x - \Delta F_s \frac{\Delta y}{\Delta s} = 0$$

Dividing through by $\Delta y\, \Delta z$ and taking the limit as the volume of the element approaches zero, we obtain

$$\lim_{\Delta V \to 0} \left[\frac{\Delta F_x}{\Delta y\, \Delta z} - \frac{\Delta F_s}{\Delta s\, \Delta z}\right] = 0$$

Recalling that normal stress is positive in tension, we obtain, by evaluating the above equation

$$\sigma_{xx} = \sigma_{ss} \tag{1-1}$$

In the y direction, applying $\Sigma \mathbf{F} = 0$ yields

$$\Delta F_y - \Delta F_s \cos\theta - \rho g \frac{\Delta x\, \Delta y\, \Delta z}{2} = 0$$

* Mathematically, stress is classed as a tensor of second order, since it requires magnitude, direction, and orientation with respect to a plane for its determination.

Since $\cos\theta = \Delta x/\Delta s$, one has

$$\Delta F_y - \Delta F_s \frac{\Delta x}{\Delta s} - \rho g \frac{\Delta x\, \Delta y\, \Delta z}{2} = 0$$

Dividing through by $\Delta x\, \Delta z$ and taking the limit as before, we obtain

$$\lim_{\Delta V \to 0} \left[\frac{\Delta F_y}{\Delta x\, \Delta z} - \frac{\Delta F_s}{\Delta s\, \Delta z} - \frac{\rho g \Delta y}{2} \right] = 0$$

which becomes

$$-\sigma_{yy} + \sigma_{ss} - \frac{\rho g}{2}(0) = 0$$

or

$$\sigma_{yy} = \sigma_{ss} \tag{1-2}$$

It may be noted that the angle θ does not appear in equation (1-1) or (1-2), thus the normal stress at a point in a static fluid is independent of direction, and is therefore a scalar quantity.

Since the element is at rest, the only surface forces acting are those due to the normal stress. If we were to measure the force per unit area acting on a submerged element, we would observe that it acts inward or to place the element in compression. The quantity measured is, of course, pressure, which in light of the preceding development, must be the negative of the normal stress. This important simplification, the reduction of stress, a tensor, to pressure, a scalar, may also be shown for the case of zero shear stress in a flowing fluid. When shearing stresses are present, the normal stress components at a point may not be equal; however, the pressure is still equal to the average normal stress; that is

$$P = -\tfrac{1}{3}(\sigma_{xx} + \sigma_{yy} + \sigma_{zz})$$

with very few exceptions, one being flow in shock waves.

Now that certain properties at a point have been discussed, let us investigate the manner in which fluid properties vary from point to point.

1.3 POINT-TO-POINT VARIATION OF PROPERTIES IN A FLUID

In the continuum approach to momentum transfer, use will be made of pressure, temperature, density, velocity, and stress fields. In previous studies the concept of a gravitational field has been introduced. Gravity, of course, is a vector, and thus a gravitational field is a vector field. In this book, vectors will be written in boldfaced type. Weather maps illustrating the pressure variation over this country are published daily in our newspapers. Since pressure is a scalar quantity, such maps are an illustration of a scalar field. Scalars in this book will be set in regular type.

In Figure 1.5 the lines drawn are the loci of points of equal pressure. The pressure, of course varies continuously throughout the region, and one may observe the pressure levels and infer the manner in which the pressure varies by examining such a map.

Of specific interest in momentum transfer is the description of the point-to-point variation in the pressure. Denoting the directions east and north in Figure 1.5 by x and y, respectively, we may represent the pressure throughout the region by the general function $P(x, y)$.