Chapter 3

Review of Fluid Mechanics

3.1 Units and Basic Definitions

Newton's Second law forms the basis of all units of measurement.
For a particle of mass m subjected to a resultant force $\vec{F}$ the law may be stated as

$$\vec{F} = m\vec{a}$$

where $\vec{a}$ is the resulting acceleration measured in a nonaccelerating frame of reference.

SI units
The SI system is a metric system based on the meter, kilogram, second and Kelvin as basic units of length, mass, time, and temperature respectively. In SI system the units for force (Newton) is derived from Newton's second law of motion. By definition one Newton is that force which will give a one-kilogram mass an acceleration of one meter per second squared. The SI system is termed an absolute system since mass is taken to be an absolute or base quantity.

English Engineering units
The English Engineering system (EES) is based on the foot, pound, second and Rankine as basic units of length, force, time, and temperature respectively. In EES the units of mass (slug) is derived from Newton's second law of motion. By definition one slug of mass will have an acceleration of one foot per second squared when acted upon by a force of one pound. EES is called a gravitational system since force (as measured from gravitational pull) is taken as a base quantity.

Quantity	SI	EES
mass	kilogram (kg)	slug
length	meter (m)	foot (ft)
time	second (s)	second (sec)
force	newton (N)	pound (lb)
Temperature	Kelvin (°K)	Rankine (°R)

System
A system is a region enclosed by a rigid or flexible boundary with a quantity of matter of fixed mass and identity. Heat and work can cross the boundary of a system.

Control volume
A control volume is a finite region in space that may be fixed or moving in space. Mass, momentum, heat and work can cross the boundary of the region called the control surface.

Phase
A phase is defined as a quantity of matter that is homogeneous throughout (ex. solid, liquid and gas).

State
A state may be defined by certain observable macroscopic properties. (ex. pressure, temperature, density, etc)

Property

A property can be defined as any quantity that depends on the state of the system and is independent of the path (i.e., the prior history) by which the system arrived at the given state. The properties of a given state are always unique. They are also called point functions.

Intensive property

Depends only on the state of the system and is independent of its mass (ex. temperature, pressure, density, etc.).

Extensive property

Depends directly with the mass of the system (ex. volume, internal energy, etc).

Process

Whenever one or more of the properties of a system change, the system has undergone a state change. The path of the succession of states through which the system passes is called the process.

Isothermal process: A constant temperature process.

Isobaric process: A constant pressure process.

Isometric process: A constant volume process.

Isentropic process: A constant entropy process.

Adiabatic process: A process with no heat transfer.

Reversible process: A reversible process is an ideal process in which the process direction can be reversed and the system would retrace the same series of equilibrium states.

Cycle

When a system in a given state goes through a number of different changes of state or processes and finally returns to its initial state, the system has undergone a cycle. Therefore, at the conclusion of a cycle all the properties have the same value they had at the beginning.

Solid

Put inside a larger, closed container will not change its shape and boundaries will remain the same.
Intermolecular loads are very rigid, maintaining the molecules in what is virtually a fixed spatial relationship. Thus a solid has a fixed volume and shape.

Liquid

Volume of liquid remains constant and takes to the general shape of the container.
Weaker bonds between the molecules. Distances between the molecules are fairly rigidly controlled but the arrangement in shape is free. A liquid, therefore has a closely defined volume but no defined shape.

Gas

Completely fill the container.
Weak bonds and has neither a defined shape nor a defined volume.

Plasma

A special form of a gas has properties different from those of a normal gas and, although belonging to the third group, can be regarded justifiably as a seperate, distinct form of matter.

Fluid

A basic feature of a fluid is that it can flow. This feature, however applies to substances which are not true fluids, e.g., a fine powder piled on a sloping surface will also flow. Heaps can be formed by flow. Thus a fluid may be defined as “matter capable of flowing and either finding its own level (if liquid) or filling the whole of its container (if a gas)”.

Microscopic point of view

In microscopic point of view we deal with the individual molecules’ motion and behavior.

Macroscopic point of view

In macroscopic point of view we are concerned with the gross or average effects of many molecules through measurable or observable properties.

Concept of a continuum: Continuum flow

From the macroscopic point of view, we are always concerned with volumes that are very large compared to molecular dimensions, and, therefore, with systems that contain many molecules. Since we are not concerned with the behavior of individual molecules, we can treat the substance as being continuous, disregarding the action of individual molecules, and this is called a continuum.

Ideal gas

Ideal gas is composed of molecules which are small compared to the mean distance between them and so the potential energy arising from their mutual attraction may be neglected. Collisions between molecules or between molecules and the containing vessel are assumed to be perfectly elastic. The average distance a molecule travels before colliding with another is termed the mean-free-path (λ). If the mean-free-path of the molecules approaches the order of magnitude of the dimensions of the vessel, then the concept of a continuum is not a valid assumption (ex. High vacuum technology, rarefied atmosphere). At temperature of 300K and above (room temperature and above) nitrogen and air behave as perfect or ideal gas up to pressure well above 1000 lb/in^2.

Free molecular flow

The mean-free-path is the same order as the body scale in this region. Vehicles such as the space shuttle encounter free molecular flow at the extreme outer edge of the atmosphere, where the air density is so low that λ becomes of the order of the shuttle size.

Low-density flow

Exhibit characteristic flow of both the Continuum flow and Free molecular flow.

Pressure-p

If a body is placed in a fluid, its surface is bombarded by a large number of molecules moving at random. When molecules bombard a surface they rebound, and by Newton's law the surface experiences a force equal and opposite to the time rate of change of momentum of the rebounding molecules. Thus $s$tatic pressure is the normal force per unit area exerted on a surface due to the time rate of change of momentum of the molecules impacting (or crossing) that surface.

$$p = \lim_{dA \to dA'} \frac{dF_n}{dA}$$

where dA' is the smallest area for which the system can be considered a continuum and dF_n is the force acting normal to that surface.
p is a point property and a scalar. p has units of (Forec/Area), N/m^2, lb/ft^2, and lb/in^2. Most pressure and vacuum gages read the difference between the absolute pressure and the atmospheric pressure existing at the gage, and this is referred as gage pressure.

Density-ρ

$$\rho = \lim_{d\not{V} \to d\not{V}'} \frac{dm}{d\not{V}}$$

where $d\not{V}'$ is the smallest volume for which the system can be considered a continuum and dm is the mass of that infinitesimal volume.

Specific volume-$\not{v}$

$$\not{v} = \lim_{d\not{V} \to d\not{V}'} \frac{d\not{V}}{dm}$$

where $d\not{V}'$ is the smallest volume for which the system can be considered a continuum.

Temperature-T

The temperature of a gas (T) is directly proportional to the average kinetic energy of the molecules of the fluid.

Note: p, ρ, T are all static properties.

Ex) A static temperature is that temperature measured by a common thermometer.

Viscosity-μ

Viscosity is that property of a fluid in ordered motion which causes their layer immediately adjacent to a surface to remain at rest.

$$\textit{Shear Stress} \quad \tau \propto \frac{du}{dy}$$

The constant of proportionality is μ.
If T is in Rankine:

$$\mu = 2.270 \times 10^{-8} \frac{T^{3/2}}{T + 198.6} \, [slug/ft \cdot sec]$$

If T is in Kelvin:

$$\mu = 1.456 \times 10^{-6} \frac{T^{3/2}}{T + 110.3} \, [kg/m \cdot sec]$$

Steady Flow

If fluid properties at a point in a field do not change with time, then they are a function of space only. They are represented by:

$$\varphi = \varphi(q_1, q_2, q_3)$$

Therefore for a steady flow $\frac{\partial\varphi}{\partial t} = 0$.

One-, Two-, and Three-Dimensional Flows

A flow is classified as one-, two-, or three-dimensional depending on the number of space coordinates required to specify all the fluid properties and the number of components of the velocity vector. For example a steady three-dimensional flow requires three space coordinates to specify the property and the velocity vector is given by: $\vec{V} = v_1\hat{e}_1 + v_2\hat{e}_2 + v_3\hat{e}_3$. Most real flows are three-dimensional in nature. On the other hand any property of a two-dimensional flow field requires only two space coordinates to describe it and its velocity has only two components along the two space coordinates that describe the field. The third component of velocity is identically zero everywhere. Steady channel flow between two parallel plates is a perfect example of two-dimensional flow if the viscous effects on the plates are neglected. The properties of the flow can be uniquely represented by $\varphi = \varphi(q_1, q_2)$ and the velocity vector can be written as $\vec{V} = v_1\hat{e}_1 + v_2\hat{e}_2$. The complexity of analysis increases considerably with the number of dimensions of the flow field. In one-dimensional flow properties vary only as a function of one spatial coordinate and the velocity component in the other two directions are identically zero. In other words $\varphi = \varphi(q_1)$ and $\vec{V} = v_1\hat{e}_1$.

Flux

Flux is defined as a rate of flow of any quantity per unit area across a control surface. Thus mass flux is the rate of mass flow rate per unit area and heat flux is the heat flow rate per unit area across the control surface.

Incompressible

If density is constant, the flow is called incompressible. If the density is variable it is called compressible flow. Flow of homogeneous liquid is treated as incompressible.

Boundary layer

The boundary layer is that region near the surface of a body where viscous effects are important.

$$\textit{Shear Stress} \quad (\tau)_{wall} = (\tau)_{y=0} = \mu \left(\frac{\partial u}{\partial y}\right)_{y=0} \text{ is large because } \left(\frac{\partial u}{\partial y}\right)_{y=0} \text{ is large.}$$

Effect of viscosity

- The speed of flow which increases from zero at the surface of the body to the full streaming speed away from the body. (Velocity gradient inside the boundary layer)
- Apparently steady force called the "skin friction drag" acting on the body in the direction of flow.

Newtonian versus Non-Newtonian fluid

Fluids for which the shear stress is directly proportional to the rate of strain are called Newtonian fluids.

$$\textit{Shear Stress} \quad (\tau) \propto \left(\frac{du}{dy}\right)$$

For same fluids, however, the shear stress may not be directly proportional to the rate of strain.

$$\textit{Shear Stress} \quad (\tau) \;\; \textit{not proportional to} \;\; \left(\frac{du}{dy}\right)$$

These fluids are classified as Non-Newtonian. ex) blood, certain plastics, clay-waste mixture.

Viscosity is important in the boundary layer, the separated flow region, and the wake region. Rest of the regions can be essentially treated as inviscid where $\mu = 0$. Inviscid theory can adequately predict the pressure distribution and lift on a body. Inviscid theory gives also a valid representation of the streamlines and flow field away from the body. Inviscid theory can not predict any drag that depends on the friction.

Classification based on approximations of flow problems

Gas is a compressible, viscous, inhomogeneous substance, and the physical principles underlying its behavior are not completely enough understood to permit us to formulate exactly, any flow problem. Even if this were possible, the resulting equations would, in all probability be too difficult to solve. Hence all formulations are approximate at best.

1. Perfect fluid: homogeneous (not composed of discrete particles), incompressible (inelastic), inviscid fluid. The assumption of a perfect fluid gives good agreement with experiment for flows outside of boundary layer and wake of well-streamlined bodies moving with velocities of less than 200 mph at altitudes under about 100,000 ft.

2. Compressible, inviscid fluid: Fluid is considered compressible (elastic) and hence speed of sound characterzies the flow. It provides a good approximation for problems involving the flow outside of boundary layer and wake of bodies for *all speeds* at altitudes below about 100,000 ft.

3. Viscous, compressible fluid: Viscosity is included. Flow within the boundary layer and wake is amenable to accurate analysis, provided the flow is laminar (good for all speeds below altitudes of 100,000 ft).