Introduction

A fluid cannot resist a shear stress by a static deflection and it moves and deforms continuously as long as the shear stress is applied.

Fluid mechanics is the study of fluids either in motion (fluid dynamics) or at rest (fluid statics). Both liquids and gases are classified as fluids.

There is a theory available for fluid flow problems, but in all cases it should be backed up by experiment. It is a highly visual subject with good instrumentation.

Since the earth is 75% covered with water and 100% with air, the scope of fluid mechanics is vast and has numerous applications in engineering and human activities. Examples are medical studies of breathing and blood flow, oceanography, hydrology, energy generation. Other engineering applications include: fans, turbines, pumps, missiles, airplanes to name a few.

The basic equations of fluid motion are too difficult to apply to arbitrary geometric configurations. Thus most textbooks concentrate on flat plates, circular pipes, and other simple geometries. It is possible to apply numerical techniques to complex geometries, this branch of fluid mechanics is called computational fluid mechanics (CFD). Our focus, however, will be on theoretical approach in this course.

Viscosity is an internal property of a fluid that offers resistance to flow. Viscosity increases the difficulty of the basic equations. It also has a destabilizing effect and gives rise to disorderly, random phenomena called turbulence.

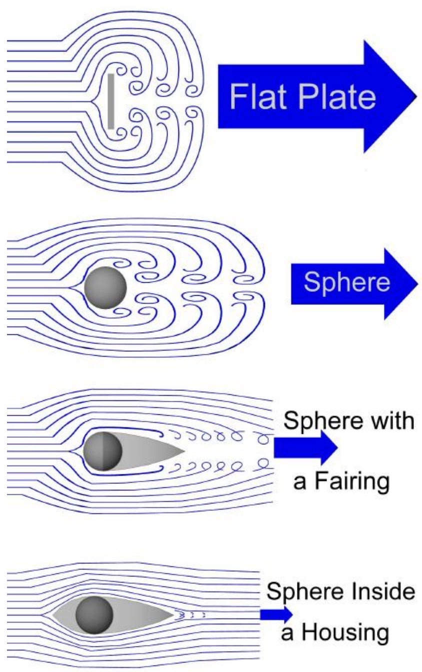

Fig.1: effects of viscosity and shape on the fluid flow.

History of fluid mechanics

Ancient civilization had enough knowledge to solve certain flow problems, e.g. sailing ships with oars, irrigation systems.

Archimedes (285 – 212 B.C.) postulated the parallelogram law for addition of vectors and the laws of buoyancy and applied them to floating and submerged objects.

Leonardo da Vinci (1452 – 1519) stated the equation of conservation of mass in one-dimensional steady-state flow. He experimented with waves, jets, hydraulic jumps, eddy formation, etc.

Edme Mariotte (1620 – 1684) built the first wind tunnel and tested models in it.

Isaac Newton (1642 – 1727) postulated his laws of motion and the law of viscosity of linear fluids, now called *newtonian*. The theory first yield the frictionless assumption which led to several beautiful mathematical solutions.

Leonhard Euler (1707 – 1783) developed both the differential equations of motion and their integral form, now called Bernoulli equation.

William Froude (1810 – 1879) and his son developed laws of model testing and Lord Rayleigh (1842 – 1919) proposed dimensional analysis.

Osborne Reynolds (1842 – 1912) published the classic pipe experiment and showed the importance of the dimensionless Reynolds number, named after him.

Navier (1785 – 1836) and *Stokes* (1819 – 1903) added newtonian viscous term to the equation of motion, the fluid motion governing equation, i.e., Navier-Stokes equation is named after them.

Ludwig Prandtl (1875 – 1953) pointed out that fluid flows with small viscosity, such as water flows and airflows, can be divided into a thin viscous layer (or boundary layer) near solid surfaces and interfaces, patched onto a nearly inviscid outer layer, where the Euler and Bernoulli equations apply.

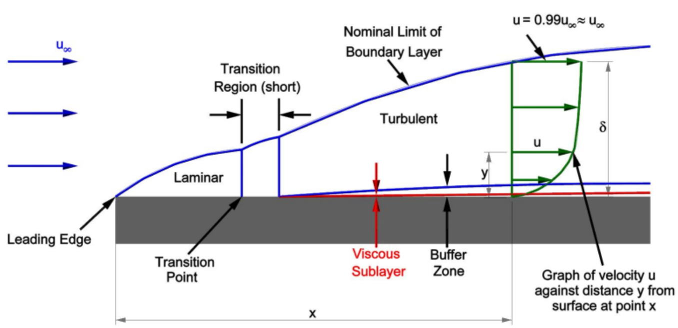

Fig. 2: The concept of boundary layer.

The concept of fluid

There are two classes of fluids:

Liquids: are composed of relatively close-packed molecules with strong cohesive forces. Liquids have constant volume (almost incompressible) and will form a free surface in a gravitational field if unconfined from above.

Gases: molecules are widely spaced with negligible cohesive forces. A gas is free to expand until it encounters confining walls. A gas has no definite volume, and it forms an atmosphere when it is not confined. Gravitational effects are rarely concerned.

Liquids and gases can coexist in two-phase mixtures such as steam-water mixtures.

We can define fluid properties and parameters, as continuous point functions, ONLY if the continuum approximation is made. This requires that the physical dimensions are large compared to the fluid molecules.

The fluid density is defined as:

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

where the δV^* is a limiting volume above which molecular variations are not important, this volume for all liquids and gases is about 10^{-9} mm^3.

Dimensions and units

Any physical quantity can be characterized by *dimensions*. The arbitrary magnitudes assigned to the dimensions are called *units*. There are two types of dimensions, *primary* or fundamental and secondary or *derived* dimensions. Some primary dimensions are: **mass**, m; **length,** L; **time,** t; **temperature,** T. Secondary dimensions are the ones that can be derived from primary dimensions such as: velocity (*m/s*), pressure ($Pa = kg/m.s^2$).

There are two unit systems currently available SI (International System) and USCS (United States Customary System) or English system. We, however, will use SI units exclusively in this course. The SI system is based on 7 fundamental units: **length**, meter (*m*); **mass**, kilogram (*kg*); **time**, second (*s*); **electric current,** ampere (*A*); **amount of light**, candela (*cd*); **amount of matter**, mole (*mol*).

The SI units are based on decimal relationship between units. The prefixes used to express the multiples of the various units are listed in Table 1.

Table 1: Standard prefixes in SI units.

MULTIPLE	10^{12}	10^{9}	10^{6}	10^{3}	10^{-2}	10^{-3}	10^{-6}	10^{-9}	10^{-12}
PREFIX	tetra, T	giga, G	mega, M	kilo, k	centi, c	mili, m	micro, µ	nano, n	pico, p

Important note: in engineering all equations must be dimensionally homogenous. This means that every term in an equation must have the same units. It can be used as a sanity check for your solution.

Example 1: Unit Conversion

The heat dissipation rate density of an electronic device is reported as 10.72 mW/mm^2 by the manufacturer. Convert this to W/m^2.

$$10.72 \frac{mW}{mm^2} \times \left(\frac{1000mm}{1m}\right)^2 \times \frac{1W}{1000mW} = 10720 \frac{W}{m^2}$$

Eulerian and Lagrangian Point of View

There are two different points of view in analyzing problems in mechanics.

In the Eulerian point of view, the dynamic behavior of the fluid is studied from a fixed point in space. Therefore, fluid properties and parameters are computed as filed functions, e.g. $p(x,y,z,t)$. Most measurement devices work based on Eulerian method.

The system concept represents a Lagrangian point of view where the dynamic behavior of a fluid particle is considered. To stimulate a Lagrangian measurement, the probe would have to move downstream at the fluid particle speed.

Fluid velocity field

Velocity: the rate of change of fluid position at a point in a flow field. Velocity in general is a vector function of position and time, thus has three components *u*, *v*, and *w*, each a scalar field in itself:

$$V(x, y, z, t) = u(x, y, z, t)i + v(x, y, z, t)j + w(x, y, z, t)k$$

Velocity is used to specify flow filed characteristics, flow rate, momentum, and viscous effects for a fluid in motion. Furthermore, velocity field must be known to solve heat and mass transfer problems.

Thermodynamic properties of a fluid

Any *characteristic* of a system is called a property. In this course, the fluid is assumed to be a *continuum*, homogenous matter with no microscopic holes. This assumption holds as long as the volumes, and length scales are large with respect to the intermolecular spacing.

Thermodynamic properties describe the state of a system.

System is defined as a collection of matter of fixed identity that interacts with its surroundings.

For a single-phase substance such as water or oxygen, two basic (independent) properties such as pressure and temperature can identify the state of a system; and thus the value of all other properties.

Note: In this course, important non-equilibrium effects such as chemical, nuclear, and magnetic effects are neglected.

Temperature

Temperature is a measure of the internal energy, it is also a pointer for the direction of energy transfer as heat.

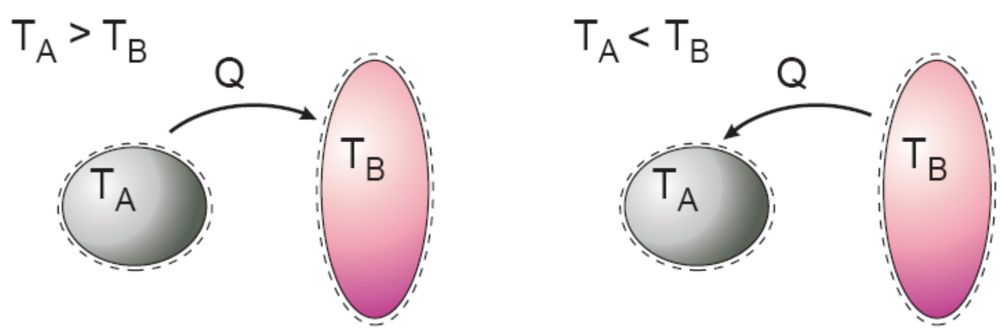

Fig. 1: Heat transfer occurs in the direction of higher-to-lower-temperature.

When the temperatures of two bodies are the same, thermal equilibrium is reached. The equality of temperature is the only requirement for thermal equilibrium.

Experimentally obtained Temperature Scales, the *Celsius* and *Fahrenheit* scales, are based on the melting and boiling points of water. They are also called *two-point scales*.

Conventional thermometry depends on material properties e.g. mercury expands with temperature in a repeatable and predictable way.

Thermodynamic Temperature Scales (independent of the material), the *Kelvin* and *Rankine* scales, are determined using a constant volume gas thermometer. The relationships between these scales are:

$$T(K) = T(^\circ C) + 273.15$$

$$T(R) = T(^\circ F) + 459.67$$

$$T(R) = 1.8T(K)$$

$$T(^\circ F) = 1.8T(^\circ C) + 32$$