G. PULLAIAH COLLEGE OF ENGINEERING AND TECHNOLOGY

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Nandikotkur Road, Venkayapalli, Kurnool – 518452

Department of Civil Engineering

Bridge Course

On

Fluid Mechanics

Course Description:

Topics covered in the course include pressure, hydrostatics, and buoyancy; open systems and control volume analysis; mass conservation and momentum conservation for moving fluids; viscous fluid flows, flow through pipes; dimensional analysis; boundary layers, and lift and drag on objects.

This class provides students with an introduction to principal concepts and methods of fluid mechanics. Topics covered in the course include pressure, hydrostatics, and buoyancy; open systems and control volume analysis; mass conservation and momentum conservation for moving fluids; viscous fluid flows, flow through pipes; dimensional analysis; boundary layers, and lift and drag on objects. Students will work to formulate the models necessary to study, analyze, and design fluid systems through the application of these concepts, and to develop the problem-solving skills essential to good engineering practice of fluid mechanics in practical applications.

Objectives/Learning Outcomes/Capability Development

This course contributes to the following Program Learning Outcomes

1. Understand the Fundamental fluid properties and their significance in Engineering and methods of fluid pressure measurement and calculation of forces on different surfaces.

2. Understand the concepts of buoyancy, stability of objects and to get expertise on fluid flow Problems like continuity, energy and momentum equations.

3. Know about the working of different types of devices used for the measurement of fluid flow

4. Understand flow through orifices and mouthpieces.

5. Understand the different types of pipe flow and the conditions for governing them

6. Understand the concepts of boundary layer flows

Introductory Concepts and Definitions:

Fluid Mechanics and Fluid Dynamics encompass a huge range of topics which deal with the behavior of gasses and liquids. In UE we will focus mainly on the topic subset called Aerodynamics, with a bit af Aerostatics in the beginning.

Merriam Webster's definitions:

Aerostatics:

It is a branch of statics that deals with the equilibrium of gaseous fluids and of solid bodies immersed in them.

Aerodynamics:

It is a branch of dynamics that deals with the motion of air and other gaseous fluids and with the forces acting on bodies in motion relative to such fluids.

Related older terms are **Hydrostatics and Hydrodynamics**, usually used for situations involving liquids. There is surprisingly little fundamental difference between the Aero– and Hydro– disciplines. They differ mainly in the applications (e.g. airplanes vs. ships).

Difference between a Solid and a Fluid (Liquid or Gas):

Solid: Applied tangential force/area (or shear stress) τ produces a proportional deformation angle (or strain) θ.

$$\tau = G\theta$$

The constant of proportionality G is called the elastic modulus, and has the units of force/area.

Fluid: Applied shear stress τ produces a proportional continuously-increasing deformation (or strain rate) θ.

$$\tau = \mu\theta$$

The constant of proportionality μ is called the viscosity, and has the units of force x time/area.

Properties of Fluids:

Continuum vs molecular description of fluid:

Liquids and gases are made up of molecules. Is this discrete nature of the fluid important for us? In a liquid, the answer is clearly NO. The molecules are in contact as they slide past each other, and overall act like a uniform fluid material at macroscopic scales.

In a gas, the molecules are not in immediate contact. So we must look at the mean free path, which is the distance the average molecule travels before colliding with another.

Some known data for air:

- Mean free path at 0 km (sea level) : 0.0001 mm
- Mean free path at 20 km (U2 flight) : 0.001 mm
- Mean free path at 50 km (balloons) : 0.1 mm
- Mean free path at 150 km (low orbit) : 1000 mm = 1m

The mean free path is vastly smaller than the typical dimension of any atmospheric vehicle. So even though the lift on a wing is due to the impingement of discrete molecules, we can assume the air is a continuum for the purpose of computing this lift. In contrast, computing the slight air drag on an orbiting satellite requires treating the air as discrete isolated particles.

Pressure:

Pressure p is defined as the force/area acting normal to a surface. A solid surface doesn't actually have to be present. The pressure can be defined at any point x, y, z in the fluid, if we assume that an infinitesimally small surface ΔA could be placed there at whim, giving a resulting normal force ΔFn.

Density:

Density ρ is defined as the mass/volume, for an infinitesimally small volume.

Velocity:

We are interested in motion of fluids, so velocity is obviously important. Two ways to look at this:

- Body is moving in stationary fluid – e.g. airplane in flight
- Fluid is moving past a stationary body – e.g. airplane in wind tunnel

The pressure fields and aerodynamics forces in these two cases will be the same if all else is equal. The governing equations we will develop are unchanged by a Galilean Transformation, such as the switch from a fixed to a moving frame of reference.

Consider a fluid element (or tiny “blob” of fluid) as it moves along. As it passes some point B, its instantaneous velocity is defined as the velocity at point B

V at a point = velocity of fluid element as it passes that point

This velocity is a vector, with three separate components, and will in general vary between different points and different times.

$$V(x, y, z, t) = u(x, y, z, t)\hat{\imath} + v(x, y, z, t)\ \hat{}\ k \sim (4) + w(x, y, z, t)\ \hat{k}$$

Steady and Unsteady Flows:

If the flow is steady, then p, ρ, V don’t change in time for any point, and hence can be given as p(x, y, z), ρ(x, y, z), V (x, y, z). If the flow is unsteady, then these quantities do change in time at some or all points.

For a steady flow, we can define a streamline, which is the path followed by some chosen fluid element. The figure above shows three particular streamline.

Dimensions and Units in Fluid Mechanics

A dimension is a measure of a physical variable.

- In fluid mechanics, there are four primary dimensions: mass, length, time, and temperature. Primary dimensions are defined as independent dimensions, from which all other dimensions can be obtained. They are listed below, along with their symbols.

Dimension	White's symbol	Cimbala's symbol
Mass	M	m
Length	L	L
Time	T	t
Temperature	q	T

All other dimensions in fluid mechanics (called secondary dimensions) can be constructed from combinations of these four primary dimensions.

- It is customary to use brackets around a variable to indicate its dimensions. For example "{Power}" means "the dimensions of power."

- Example - Dimensions of Force - Force is not a primary dimension in fluid mechanics. Yet, force (and any other secondary dimension used in fluid mechanics) can be written as a combination of the four primary dimensions, i.e. in terms of mass, length, time, and temperature.
- Example - Dimensions of Power - Power is not a primary dimension in fluid mechanics. Yet, power (and any other dimension used in fluid mechanics) can be written as a combination of the four primary dimensions, i.e. in terms of mass, length, time, and temperature.
- Dimensions have no numbers associated with them.
- A unit is a way to assign a number or measurement to a dimension.
- There are three primary unit systems in use:
- the International System of Units (SI units - kg, N, m, s, K)
- the English Engineering System of Units (commonly called English units - lbm, lbf, ft, s, R)
- the British Gravitational System of Units (BG - slug, lbf, ft, s, oR)
- Units must always have numbers associated with them.
- For example, length is a dimension, but it is measured in units of feet (ft) or meters (m).

Fluid Mechanics:

The study of fluids - liquids and gases, involves velocity, pressure, density and temperature as functions of space and time.

Buoyancy:

Buoyancy is defined as the tendency of a body to float or rise when submerged in a fluid. The resultant force acting on a submerged body by the fluid is called the buoyant force and can be expressed as

$F = V \gamma$

$= V \rho g$ ………………… (1)

Where

F = buoyant force (N)

V = body volume (m^3)

γ = specific weight of fluid (N/m^3)

ρ = density of fluid (kg/m^3)

g = acceleration of gravity (= 9.81 m/s^2)

The buoyant force acts upwards.

Archimedes' principle indicates that

"The upward buoyant force that is exerted on a body fully or partially submerged in a fluid - equals to the weight of the fluid that the body displaces"

- if the body weighs more than the fluid - it sinks
- if the body weighs less than the fluid - it floats

Centroid:

The centroid of a triangle is the intersection of the three medians of the triangle (each median connecting a vertex with the midpoint of the opposite side). It lies on the triangle's Euler line, which also goes through various other key points including the orthocenter and the circum-center.

The Buoyancy Force act through the Centre of Gravity of the Displaced Fluid and is called The Centre of Buoyancy

There are three Types of Equilibrium:

- **Stable**: The body returns to its original position if given a small angular displacement.
- **Neutral:** The body remains in a new position if given a small angular displacement.
- **Unstable:** The body heals further over if given a small angular displacement.

Meta Centre:

It is defined as the point where the vertical through the new Centre of Buoyancy meets the original vertical through the Centre of Gravity after a very small angle of rotation.

Fluid Kinematics:

Fluid kinematics is a field of physics and mechanics concerned with the movement of fluids. Fluids tend to flow easily, which causes a net motion of molecules from one point in space to another point as a function of time.

Fluid Dynamics:

In physics and engineering, fluid dynamics is a sub discipline of fluid mechanics that describes the flow of fluids (liquids and gases). It has several sub disciplines, including aerodynamics (the study of air and other gases in motion) and hydrodynamics (the study of liquids in motion).

Problems in fluid dynamics:

Scientists often try to visualize flow using figures called streamlines, streak lines and path lines. McDonough defines a streamline as "a continuous line within a fluid such that the tangent at each point is the direction of the velocity vector at that point." In other words, a streamline shows the direction of the flow at any particular point in the flow. A streak line, according to McDonough, is "the locus [location] of all fluid elements that have previously passed through a given point." A path line (or particle path), he writes, is "the trajectory of an individual element of fluid." If the flow does not change over time, the path line will be the same as the streamline. However, in the case of turbulent or unsteady flow, these lines can be quite different.

Most problems in fluid dynamics are too complex to be solved by direct calculation. In these cases, problems must be solved by numeric methods using computer simulations. This area of study is called numerical or computational fluid dynamics (CFD), which Southard defines as "a branch of computer-based science that provides numerical predictions of fluid flows." However, because turbulent flow tends to be nonlinear and chaotic, particular care must be taken in setting up the rules and initial conditions for these simulations. Small changes at the beginning can result in large differences in the results.

The accuracy of simulations can be improved by dividing the volume into smaller regions and using smaller time steps, but this increases computing time. For this reason, CFD should advance as computing power increases.

Basic Concepts

- Mechanics is the oldest physical science that deals with both stationery and moving boundaries under the influence of forces. The branch of the mechanics that deals with bodies at rest is called statics while the branch that deals with bodies in motion is called dynamics.
- Fluid Mechanics is the science that deals with behavior of fluids at rest (fluid statics) or in motion (fluid dynamics) and the interaction of fluids with solids or other fluids at the boundaries.
- A substance in liquid / gas phase is referred as ‘fluid’. Distinction between a solid & a fluid is made on the basis of substance’s ability to resist an applied shear (tangential) stress that tends to change its shape. A solid can resist an applied shear by deforming its shape whereas a fluid

deforms continuously under the influence of shear stress, no matter how small is its shape. In solids, stress is proportional to strain, but in fluids, stress is proportional to 'strain rate.'

Fluid as Continuum:

Fluids are aggregations of molecules; widely spaced for a gas and closely spaced for liquids. Distance between the molecules is very large compared to the molecular diameter. The number of molecules involved is immense and the separation between them is normally negligible. Under these conditions, fluid can be treated as continuum and the properties at any point can be treated as bulk behavior of the fluids.

For the continuum model to be valid, the smallest sample of matter of practical interest must contain a large number of molecules so that meaningful averages can be calculated. In the case of air at sea-level conditions, a volume of 10-9 mm3 contains 3×107 molecules. In engineering sense, this volume is quite small, so the continuum hypothesis is valid.

In certain cases, such as, very-high-altitude flight, the molecular spacing becomes so large that a small volume contains only few molecules and the continuum model fails. For all situations in these lectures, the continuum model will be valid.

Properties of Fluid:

Any characteristic of a system is called property. It may either be intensive (mass independent) or extensive (that depends on size of system). The state of a system is described by its properties. The number of properties required to fix the state of the system is given by state postulates. Most common properties of the fluid are:

1. Pressure (p) :

It is the normal force exerted by a fluid per unit area. More details will be available in the subsequent section (Lecture 02). In SI system the unit and dimension of pressure can be written as, N/m2 and -1 -2 MLT, respectively.

2. Density:

The density of a substance is the quantity of matter contained in unit volume of the substance. The units and dimensions are given as,

For mass density; Dimension: 3 M L− Unit: kg/m3

For specific weight; Dimension: -2 -2 ML T Unit: N/m3

The standard values for density of water and air are given as 1000kg/m3 and 1.2 kg/m3, respectively. Many a times the reciprocal of mass density is called as specific volume (v).

3. Temperature (T):

It is the measure of hotness and coldness of a system. In thermodynamic sense, it is the measure of internal energy of a system. Many a times, the temperature is expressed in centigrade scale (°C) where the freezing and boiling point of water is taken as 0°C and 100°C, respectively. In SI system, the temperature is expressed in terms of absolute value in Kelvin scale (K = °C+ 273)

4. Vapour pressure (pv) :

It is defined as the pressure exerted by its vapour in phase equilibrium with its liquid at a given temperature. For a pure substance, it is same as the saturation pressure. In a fluid motion, if the pressure at some location is lower than the vapour pressure, bubbles start forming. This phenomenon is called as cavitation because they form cavities in the liquid.

Classifications of Fluid Flows:

Some of the general categories of fluid flow problems are as follows;

1. Viscous and In-viscid flow:

The fluid flow in which frictional effects become signification, are treated as viscous flow. When two fluid layers move relatively to each other, frictional force develops between them which is quantified by the fluid property 'viscosity'. Boundary layer flows are the example viscous flow. Neglecting the viscous terms in the governing equation, the flow can be treated as in-viscid flow.

2. Internal and External flow:

The flow of an unbounded fluid over a surface is treated as 'external flow' and if the fluid is completely bounded by the surface, then it is called as 'internal flow'. For example, flow over a flat plate is considered as external flow and flow through a pipe/duct is internal flow. However, in special cases, if the duct is partially filled and there is free surface, then it is called as open channel flow. Internal flows are dominated by viscosity whereas the viscous effects are limited to boundary layers in the solid surface for external flows.

3. Compressible and Incompressible flow:

The flow is said to be 'incompressible' if the density remains nearly constant throughout. When the density variation during a flow is more than 5% then it is treated as 'compressible'. This corresponds to a flow Mach number of 0.3 at room temperature.

4. Laminar and Turbulent flow:

The highly ordered fluid motion characterized by smooth layers of fluid is called 'Laminar Flow', e.g. flow of highly viscous fluids at low velocities. The fluid motion that typically occurs at high velocities is characterized by velocity fluctuations are called as 'turbulent.' The flow that alternates between being laminar & turbulent is called 'transitional'. The dimensionless number i.e. Reynolds number is the key parameter that determines whether the flow is laminar or turbulent.

5. Steady and Unsteady flow:

When there is no change in fluid property at point with time, then it implies as steady flow. However, the fluid property at a point can also vary with time which means the flow is unsteady or transient. The term 'periodic' refers to the kind of unsteady flows in which the flow oscillates about a steady mean.

6. Natural and Forced flow: In a forced flow, the fluid is forced to flow over a surface by external means such as a pump or a fan. In other case (natural flow), density difference is the driving factor of the fluid flow. Here, the buoyancy plays an important role. For example, a warmer fluid rises in a container due to density difference.

7. One/Two/Three dimensional flow:

A flow field is best characterized by the velocity distribution, and thus can be treated as one/two/three dimensional flow if velocity varies in the respective directions.

Fluid Statics:

Many fluid problems do not involve motion rather concerned with the pressure distribution in a static fluid. When the fluid velocity is zero, known as hydrostatic condition, the pressure variation is due to weight of the fluid. The important areas of fluid statics include;

• Pressure distribution in atmospheres and oceans

• Design of manometer pressure instruments

• Forces on submerged flat and curved surfaces

• Buoyancy on a submerged body

• Behavior of floating bodies

Hydrostatic pressure for fluids

The term ‘pressure’ is used to indicate the normal force per unit area at a point acting on a given plane within the fluid mass of interest. It is governed by Pascal’s law which states that the pressure at a point in a fluid at rest or in motion is independent of direction as long as there is no shearing stress present.