Fluid Mechanics
Chapter 1: Introduction

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Introduction

Mechanics is the field of science focused on the motion of material bodies. Mechanics involves force, energy, motion, deformation, and material properties

***fluid mechanics*.**

***solid mechanics*.**

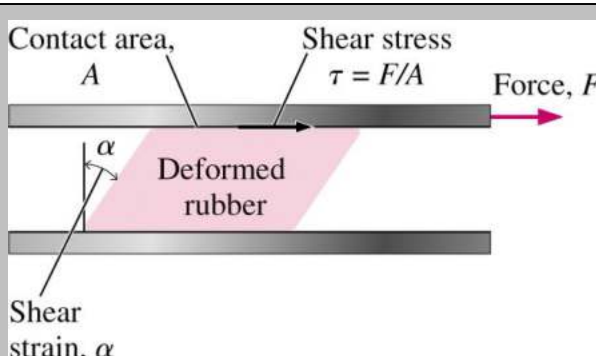
What is fluid??

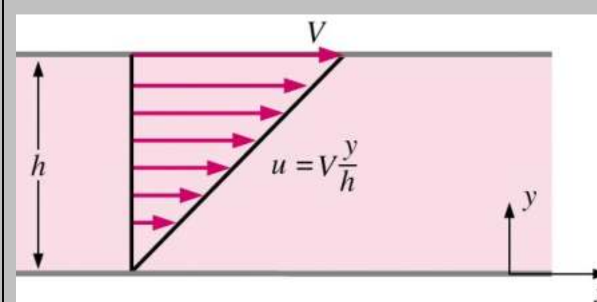
What is a fluid?

- A fluid is a substance in the gaseous or liquid form
- Distinction between solid and fluid?
  - Solid: can resist an applied shear by deforming. Stress is proportional to strain
  - Fluid: deforms continuously under applied shear. Stress is proportional to strain rate

Solid

$$\tau = \frac{F}{A} \propto \alpha$$

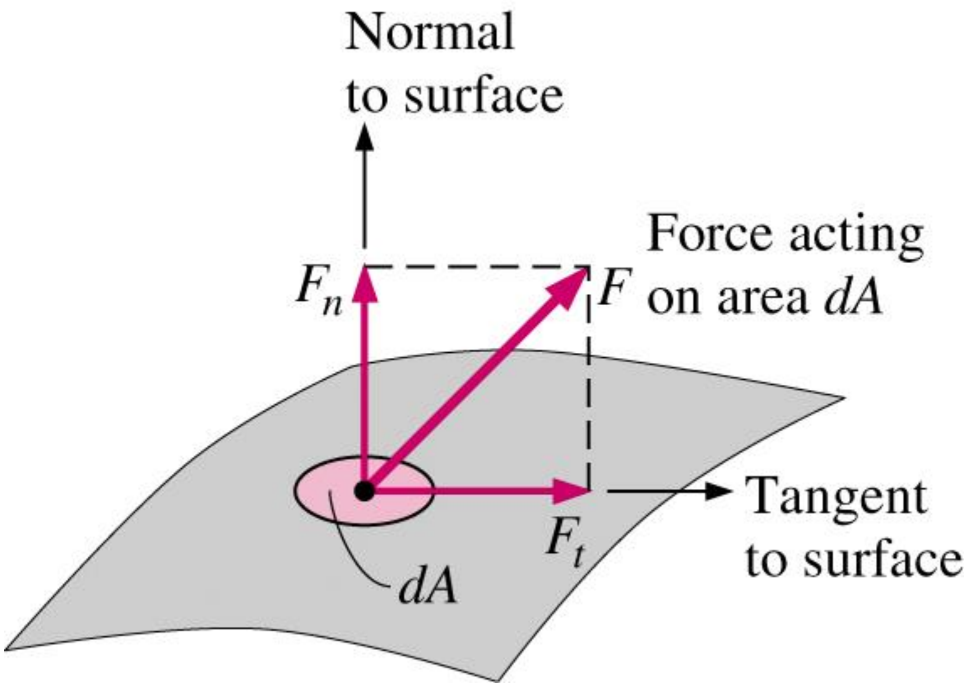




Fluid

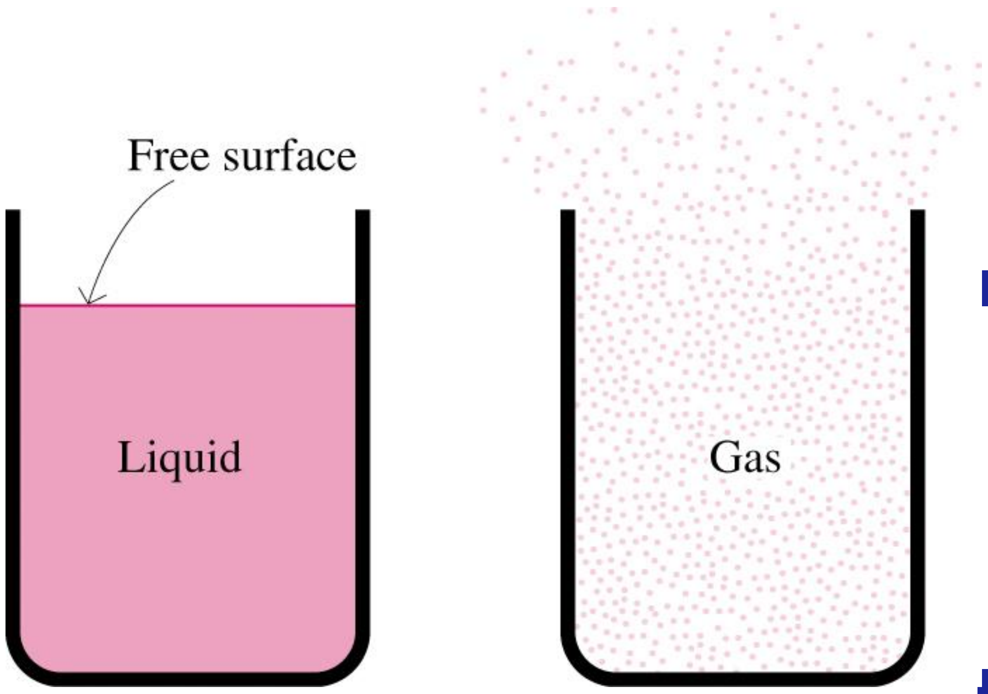
$$\tau = \frac{F}{A} \propto \mu \frac{V}{h}$$

What is a fluid?



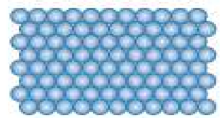
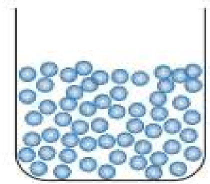
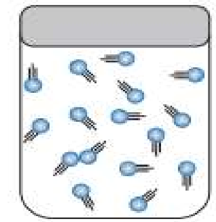
- Stress is defined as the force per unit area.
- Normal component: normal stress
  - In a fluid at rest, the normal stress is called **pressure**
- Tangential component: shear stress

What is a fluid?

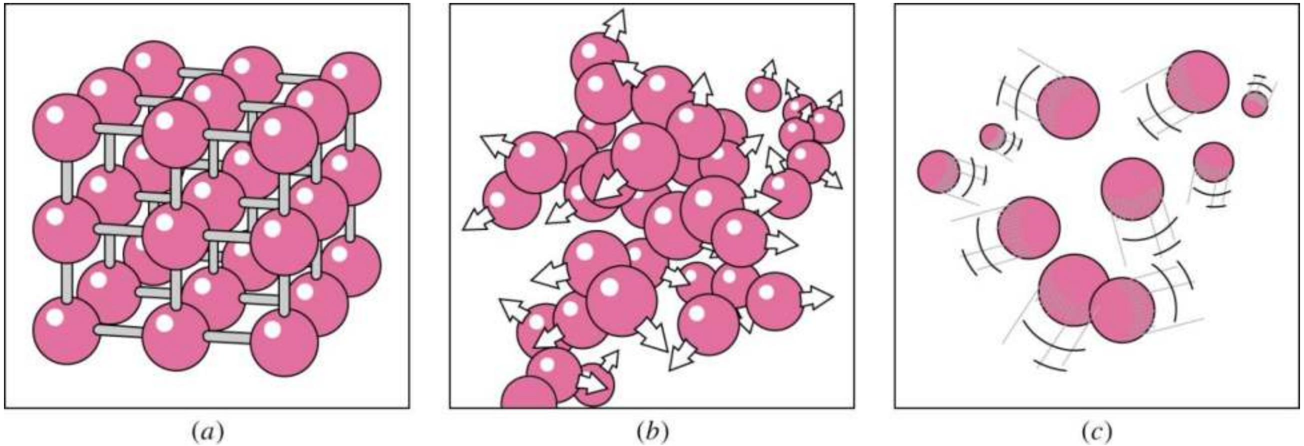


- A liquid takes the shape of the container it is in and forms a free surface in the presence of gravity
- A gas expands until it encounters the walls of the container and fills the entire available space. Gases cannot form a free surface
- Gas and vapor are often used as synonymous words

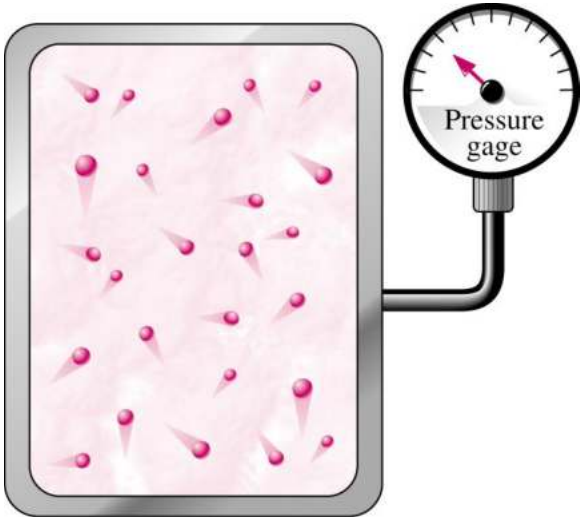
What is a fluid?

Attribute	Solid	Liquid	Gas
Typical Visualization			
Macroscopic Description	hold their shape; no need for a container	take the shape of the container	expand to fill a closed container
Mobility of Molecules	low mobility, strong bond forces	flow easily, even strong bond forces	move around freely
Typical Density	Often high; e.g. steel is 7700 kg/ m3	Medium; e.g., water 1000 kg m3	Small; e.g., air at sea level is 1.2 kg m3
Molecular Spacing	Small, close together	Small, close together	Large—on average, far apart
Effect of Shear Stress	Produces deformation	Produces flow	Produces flow
Effect of Normal Stress	Deformation, can cause failure	deformation associated with volume change	deformation associated with volume change
Viscosity		High; decreases as temperature increases	Low; increases as temperature increases

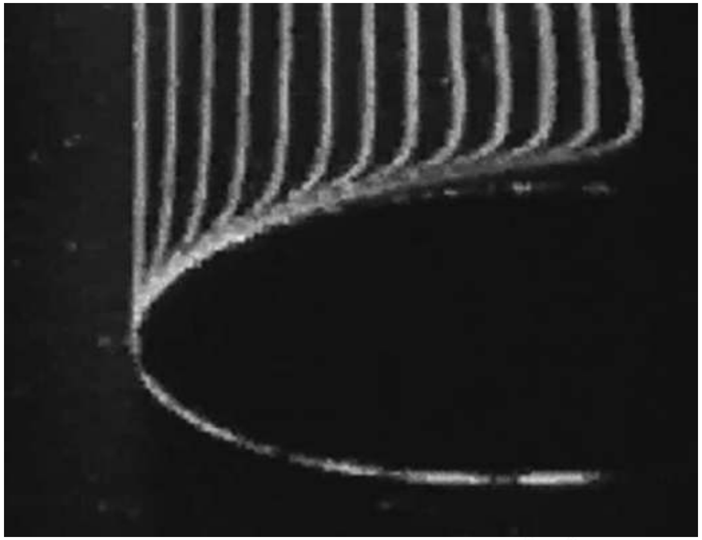
What is a fluid?

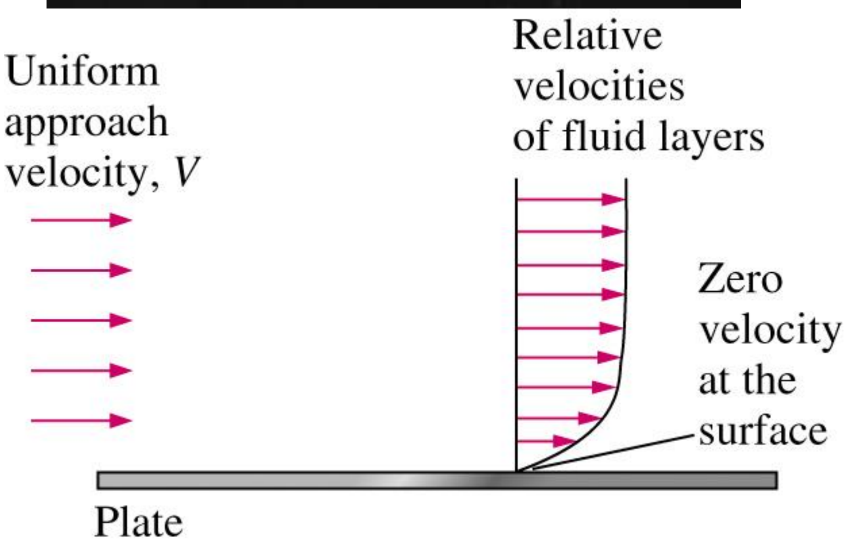


solid liquid gas



No-slip condition





- No-slip condition: A fluid in direct contact with a solid ``sticks" to the surface due to viscous effects
- Responsible for generation of wall shear stress τ_w, surface drag $D = \int \tau_w \, dA$, and the development of the boundary layer
- The fluid property responsible for the no-slip condition is **viscosity**
- Important boundary condition in formulating initial boundary value problem (IBVP) for analytical and computational fluid dynamics analysis

Classification of Flows

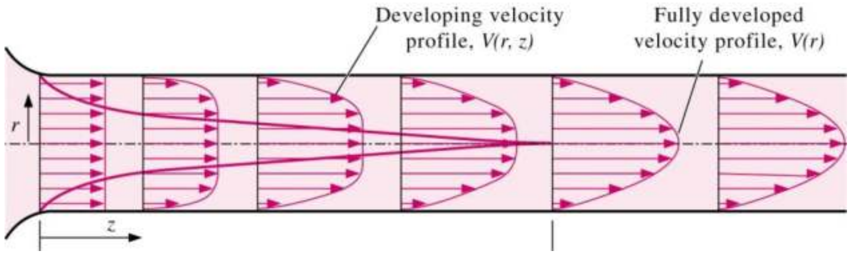
- We classify flows as a tool in making simplifying assumptions to the governing partial-differential equations, which are known as the Navier-Stokes equations
  - Conservation of Mass

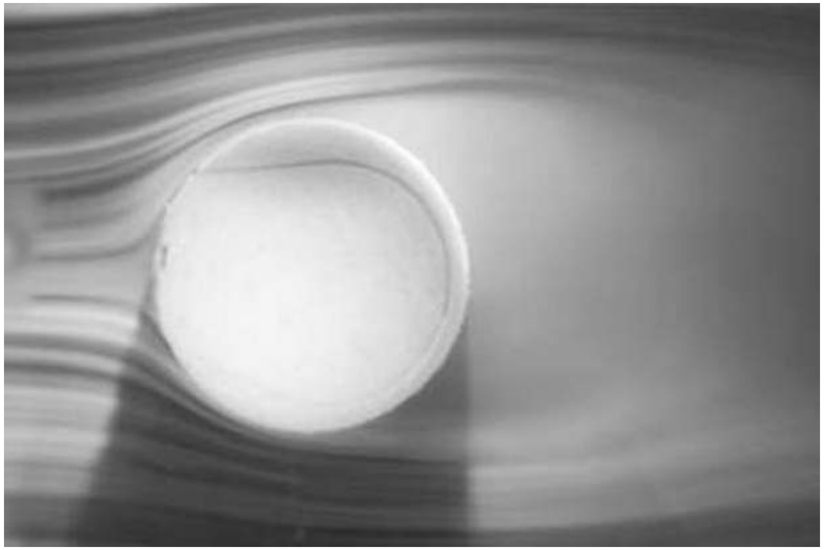
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0$$

  - Conservation of Momentum

$$\rho \frac{\partial \mathbf{U}}{\partial t} + (\mathbf{U} \cdot \nabla)\,\mathbf{U} = -\nabla p + \rho \mathbf{g} + \mu \nabla^2 \mathbf{U}$$

Internal vs. External Flow





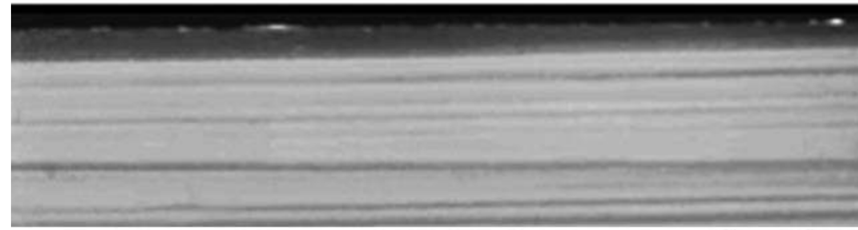
- Internal flows are dominated by the influence of viscosity throughout the flowfield
- For external flows, viscous effects are limited to the boundary layer

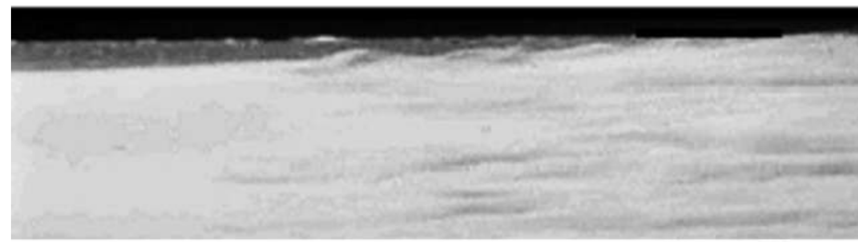
Compressible vs. Incompressible Flow

- A flow is classified as incompressible if the density remains nearly constant.
- Liquid flows are typically incompressible.
- Gas flows are often compressible, especially for high speeds.
- Mach number, Ma = V/c is a good indicator of whether or not compressibility effects are important.
  - Ma < 0.3 : Incompressible
  - Ma < 1 : Subsonic
  - Ma = 1 : Sonic
  - Ma > 1 : Supersonic
  - Ma >> 1 : Hypersonic

Laminar vs. Turbulent Flow

- Laminar: highly ordered fluid motion with smooth streamlines.
- Turbulent: highly disordered fluid motion characterized by velocity fluctuations and eddies.
- Transitional: a flow that contains both laminar and turbulent regions
- Reynolds number, Re= $\rho UL/\mu$ is the key parameter in determining whether or not a flow is laminar or turbulent.


Laminar


Transitional


Turbulent

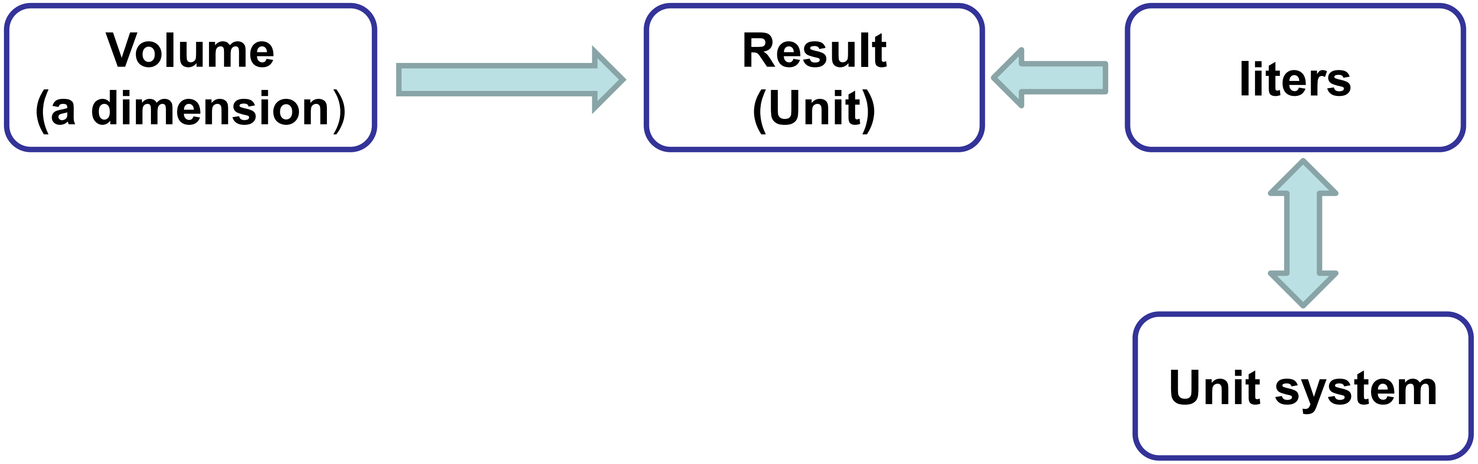
Dimensions

- A *dimension* is a category that represents a physical quantity such as:
- mass, length, time These called Primary dimensions
- Secondary dimensions such as momentum and energy Force can be related to primary dimensions by using equations
- Example:

- $F = [ma] = M\frac{L}{T^2} = \frac{ML}{T^2}$

Units

- While a dimension expresses a specific type of physical quantity, a unit assigns a number so that the dimension can be measured
- Examples:



Unit Systems

Unit Systems

- The International System (SI)
- English Engineering System

Table 1.2 PRIMARY DIMENSIONS

Dimension	Symbol	Unit (SI)
Length	*L*	meter (m)
Mass	*M*	kilogram (kg)
Time	*T*	second (s)
Temperature	θ	kelvin (K)
Electric current	*i*	ampere (A)
Amount of light	*C*	candela (cd)
Amount of matter	*N*	mole (mol)

pound-mass (lbm) for mass

the foot (ft) for length the

the second (s) for time

F or Temperature

Dimensionless Groups

- A *dimensionless group* is any arrangement of variables in which the primary dimensions cancel
- Example:

Mach Number, M

$$M = \frac{V}{C} = \frac{LT^{-1}}{LT^{-1}} = [-]$$

Dimensionless Groups

Example: Show that the Reynolds number equation is a dimensionless group

$$Re = \frac{\rho V L}{\mu} = [-]$$

Primary dimensions

$$[\rho] = M/L^3$$
$$[V] = L/T$$
$$[L] = L$$
$$[\mu] = M/LT$$

$$\left[\frac{\rho V L}{\mu}\right] = \left[\frac{M}{L^3}\right]\left[\frac{L}{T}\right][L]\left[\frac{LT}{M}\right] = [-]$$

Since the primary dimensions cancel, the Reynolds number is a dimensionless group.

Dimensional Homogeneity

- When the primary dimensions on each term of an equation are the same, the equation is ***dimensionally homogeneous***
- Example

Show that the ideal gas law is dimensionally homogeneous

P= ρRT

$$[p] = \frac{M}{LT^2}$$

$$[\rho] = M/L^3$$

$$[R] = L^2/\theta T^2$$

$$[T] = \theta$$

$$[\rho RT] = \left(\frac{M}{L^3}\right)\left(\frac{L^2}{\theta T^2}\right)(\theta) = \frac{M}{LT^2}$$

Conclusion: The ideal gas law is dimensionally homogeneous because the primary dimensions of each term are the same.

Dimensional Homogeneity

- The primary dimensions for a higher-order derivative can also be found by using the basic definition of the derivative

EXAMPLE 1.3 PRIMARY DIMENSIONS OF A DERIVATIVE AND INTEGRAL

Find the primary dimensions of $\mu \frac{d^2 u}{dy^2}$, where μ is viscosity, u is fluid velocity, and y is distance. Repeat for $\frac{d}{dt}\int_{\forall} \rho \, d\forall$ where t is time, $\forall$ is volume, and ρ is density.

Dimensional Homogeneity

Solution

1. Primary dimensions of $\mu \dfrac{d^2u}{dy^2}$
   - From Table A.6:

$$[\mu] = M/LT$$
$$[u] = L/T$$
$$[x] = L$$

   - Apply Eq. (1.5):

$$\left[\frac{d^2u}{dy^2}\right] = \left[\frac{u}{y^2}\right] = \frac{L/T}{L^2}$$

   - Combine the previous two steps:

$$\left[\mu\frac{d^2u}{dy^2}\right] = [\mu]\left[\frac{d^2u}{dy^2}\right] = \left(\frac{M}{LT}\right)\left(\frac{L/T}{L^2}\right) = \boxed{\frac{M}{L^2T^2}}$$

Dimensional Homogeneity

2. Primary dimensions of $\frac{d}{dt}\int_{V} \rho \, dV$

- Find primary dimensions from Table A.6:

$$[t] = T$$

$$[\rho] = M/L^3$$

$$[V] = L^3$$

- Apply Eqs. (1.5) and (1.6) together:

$$\left[\frac{d}{dt}\int_{V} \rho \, dV\right] = \left[\frac{\rho V}{t}\right] = \left(\frac{M}{L^3}\right)\left(\frac{L^3}{T}\right) = \boxed{\frac{M}{T}}$$

Dimensions and Units (Summary)

- Any physical quantity can be characterized by **dimensions**.
- The magnitudes assigned to dimensions are called **units**.
- Primary dimensions include: mass m, length L, time t, and temperature T.
- Secondary dimensions can be expressed in terms of primary dimensions and include: velocity V, energy E, and volume V.
- Unit systems include English system and the metric SI (International System). We'll use both.
- **Dimensional homogeneity** is a valuable tool in checking for errors. Make sure every term in an equation has the same units.
- **Unity conversion ratios** are helpful in converting units. Use them.

Accuracy, Precision, and Significant Digits

Engineers must be aware of three principals that govern the proper use of numbers.

1. ***Accuracy error :*** Value of one reading minus the true value. Closeness of the average reading to the true value. Generally associated with repeatable, fixed errors.
2. ***Precision error :*** Value of one reading minus the average of readings. Is a measure of the fineness of resolution and repeatability of the instrument. Generally associated with random errors.
3. ***Significant digits :*** Digits that are relevant and meaningful. When performing calculations, the final result is only as precise as the least precise parameter in the problem. When the number of significant digits is unknown, the accepted standard is 3. Use 3 in all homework and exams.