ENSC 283

Introduction and Properties of Fluids

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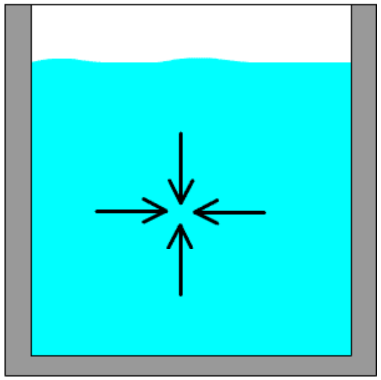
Prepared by:
M. Bahrami
Mechatronics System Engineering, School of Engineering and Sciences, SFU

Pressure

- Pressure is the (compression) force exerted by a fluid per unit area.

$$Pressure = \frac{Force}{Area} \quad \left(\frac{N}{m^2}\right) \equiv Pa$$

- Stress vs. pressure?
- In fluids, gases and liquids, we speak of pressure; in solids this is normal stress. For a fluid at rest, the pressure at a given point is the same in all directions.



- Differences or gradients in pressure drive a fluid flow, especially in ducts and pipes.

Density

- The density of a fluid is its mass per unit volume:

$$\rho = \frac{m}{V} \quad \left(\frac{kg}{m^3}\right)$$

- Liquids are essentially incompressible
- Density is highly variable in gases nearly proportional to the pressure.

@20˚C, 1 atm	Air	Water	Hydrogen	Mercury
Density (kg/m^3)	1.20	998	0.0838	13,580

- **Note**: *specific volume* is defined as:

$$v = \frac{V(m^3)}{m(kg)} = \frac{1}{\rho}$$

Specific weight

- The specific weight of a fluid is its weight, , per unit volume. Density and specific weight are related by gravity:

$$\gamma = \rho g \quad \left(\frac{N}{m^3}\right)$$

Specific gravity

- Specific gravity is the ratio of a fluid density to a standard reference fluid, typically water at 4˚C (for liquids) and air (for gases):

$$SG_{gas} = \frac{\rho_{gas}}{\rho_{air}} = \frac{\rho_{gas}}{1.205\ (kg/m^3)}$$

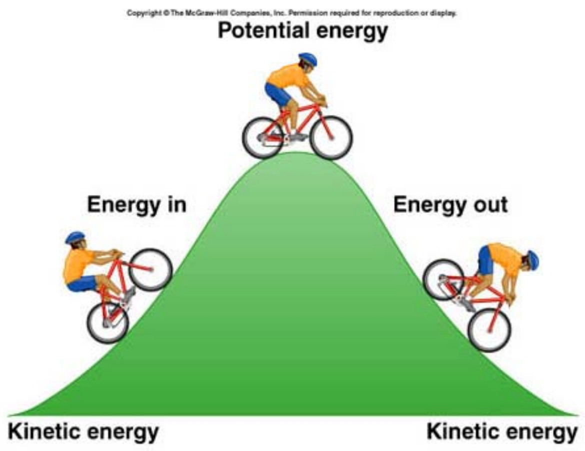
$$SG_{liquid} = \frac{\rho_{liquid}}{\rho_{water}} = \frac{\rho_{liquid}}{1000\ (kg/m^3)}$$

- For example, the specific gravity of mercury is SG_{Hg} = 13,580/1000 $\cong$ 13.6.

SFU Kinetic and potential energy

- Potential energy is the work required to move the system of mass *m* from the origin to a position against a gravity field *g*:

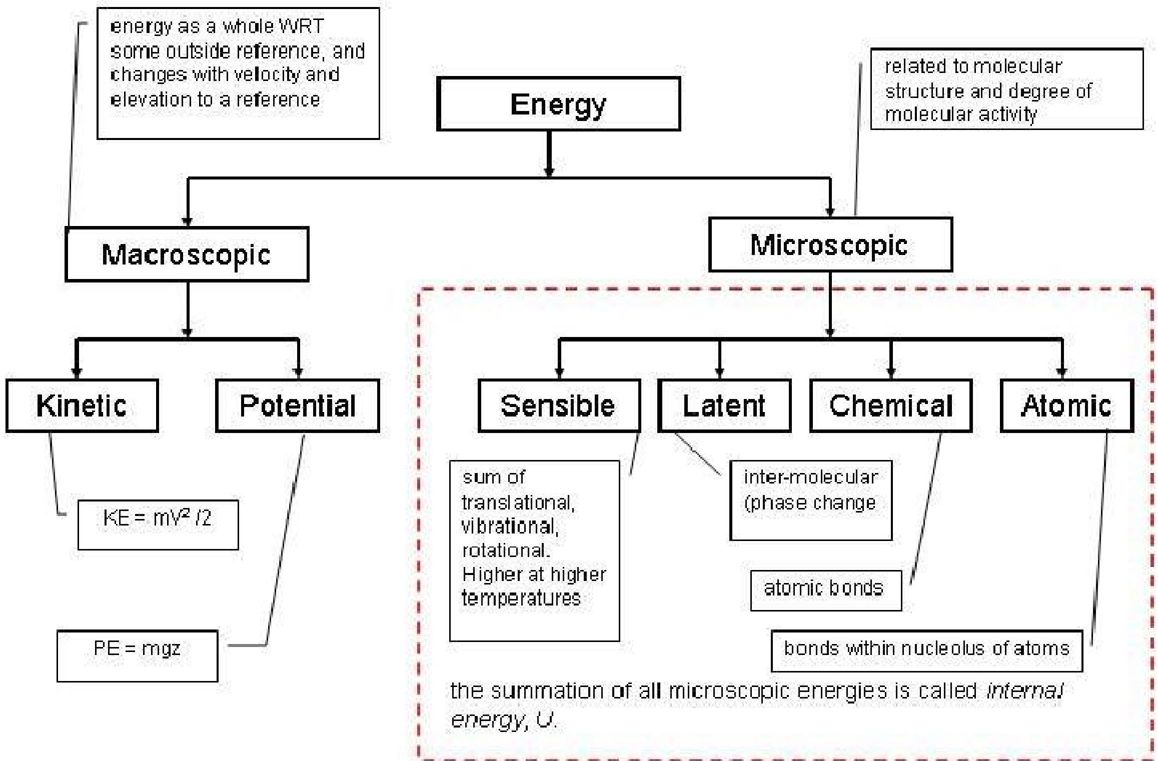
$$PE = mgz$$



- Kinetic energy is the work required to change the speed of the mass from zero to velocity *V*.

$$KE = \frac{1}{2} m V^2$$

Energy

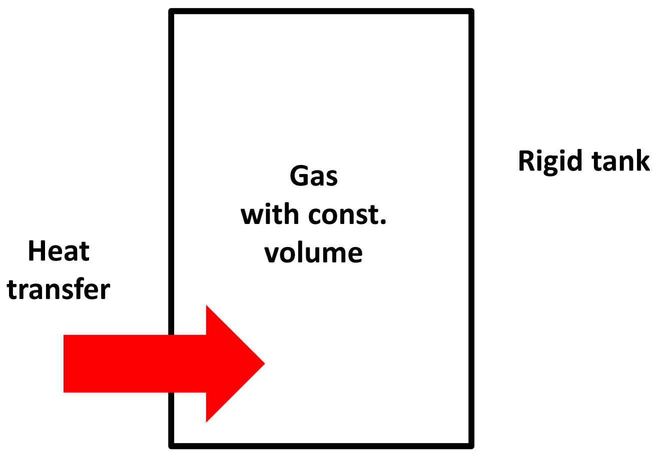


$$E = U + KE + PE \qquad (kJ)$$

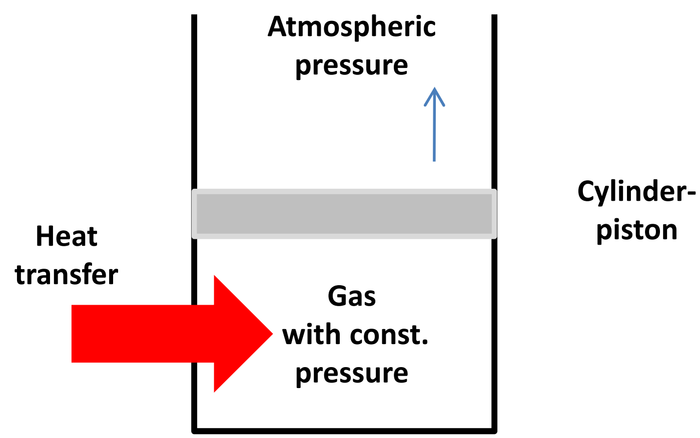
- <u>Note</u>: internal energy, *u*, is a function of temperature and pressure for the single-phase substance, whereas KE and PE are kinematic quantities.

Specific heat

- Specific heat capacity: is the measure of the heat energy required to increase the temperature of a unit mass of a substance by one degree temperature.
- $c_{aluminum}$ =0.9 (kJ/kg.K) and c_{water} = 4.186 (kJ/kg.K)
- There are two types of specific heats, constant volume c_v and constant pressure c_p.



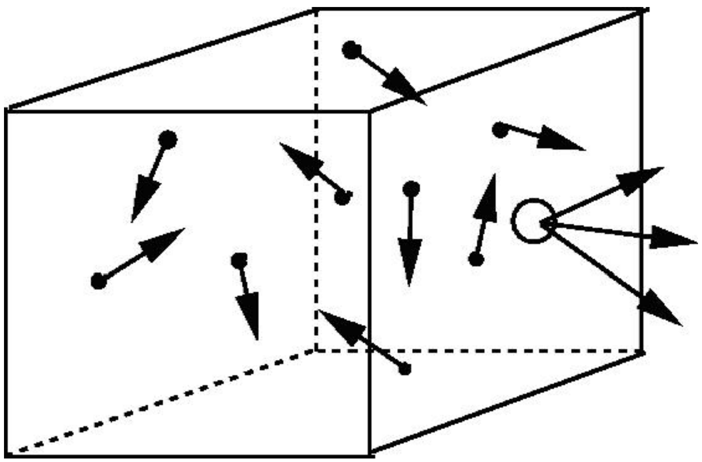
c_v



c_p

Ideal gas equation of state

- Any equation that relates the pressure, temperature, and specific volume of a substance is called an equation of state.
- It is experimentally observed that at a low pressure the volume of a gas is proportional to its temperature:



$$p = R_u \rho T$$

$$p = \rho R T$$

R_u is the gas universal constant, R_u = 8.314 (*kJ/kmol.K*)

The constant R is different for each gas; for air, R_{air} = 0.287 (*kJ/kg.K)*. The molecular weight of air M=28.97 *kg/kmol*.

Properties of ideal gas

- For an ideal gas, *internal energy* is only a function of temperature; thus constant volume specific heat is only a function of temperature:

$$c_v = \left(\frac{\partial u}{\partial T}\right)\bigg|_v = \frac{du}{dT} = c_v(T)$$

$$du = c_v(T)dT$$

- For an ideal gas, *enthalpy* is only a function of temperature; *h= u + pv*
- The constant pressure specific heat can be defined as:

$$c_p = \left(\frac{\partial h}{\partial T}\right)\bigg|_p = \frac{dh}{dT} = c_p(T)$$

$$dh = c_p(T)dT$$

$$R = c_p - c_v$$

- The specific heat ratio is an important dimensionless parameter:

$$k = \frac{c_p}{c_v} = k(T) \geq 1$$

Incompressible fluids

- Liquids are (almost) incompressible and thus have a single constant specific heat:

$$c_p = c_v = c \qquad dh = c\,dT$$

Viscosity

- Viscosity is a measure of a fluid's resistance to flow. It determines the fluid strain rate that is generated by a given applied shear stress.

- Temperature has a strong and pressure has a moderate effect on viscosity. The viscosity of gases and most liquids increases slowly with pressure.

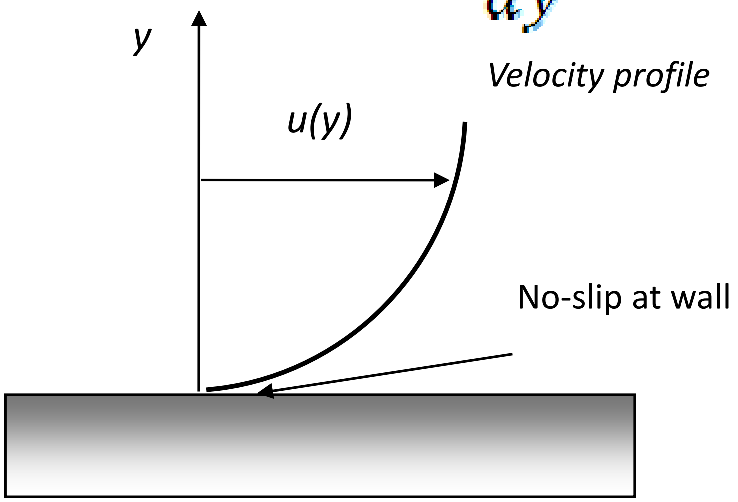
$$\mu_{hydrogen} = 9.0E-6 \left(\frac{kg}{m.s}\right) \qquad \mu_{air} = 1.8E-5 \left(\frac{kg}{m.s}\right)$$

$$\mu_{water} = 1.0E-3 \left(\frac{kg}{m.s}\right) \qquad \mu_{engine\ oil,SAE30} = 0.20 \left(\frac{kg}{m.s}\right)$$

Viscosity

- A Newtonian fluid has a linear relationship between shear stress and velocity gradient:

$$\tau = \mu \frac{du}{dy}$$

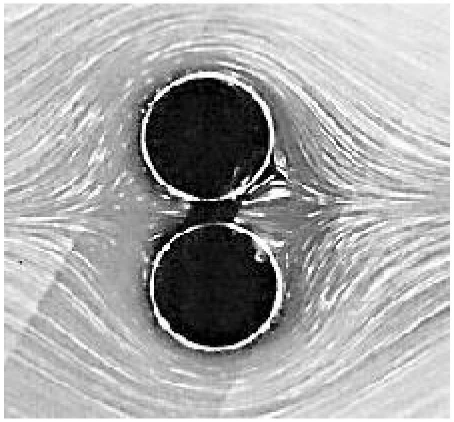


- The *no-slip condition*: at the wall velocity is zero relative to the wall. This is a characteristic of all viscous fluid.
- The shear stress is proportional to the slope of the velocity profile and is greatest at the wall.

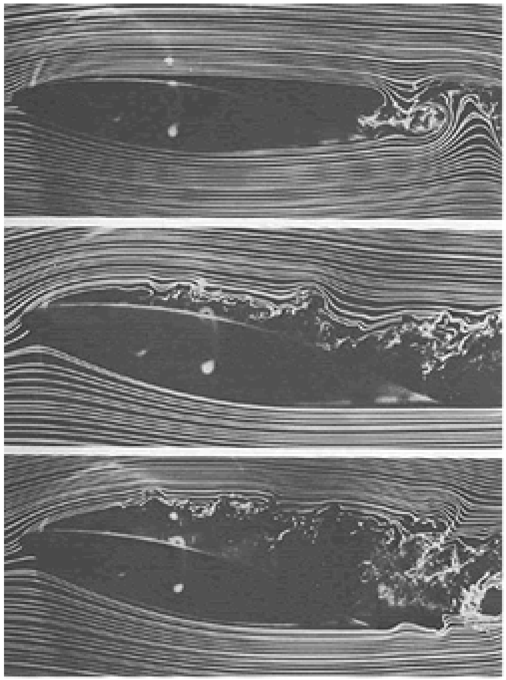
The Reynolds number

- The Reynolds number, *Re*, is a dimensionless number that gives a measure of the ratio of inertial forces to viscous forces

$$Re = \frac{\rho V L}{\mu} = \frac{V L}{\nu}$$



Creeping flow, Re is very low



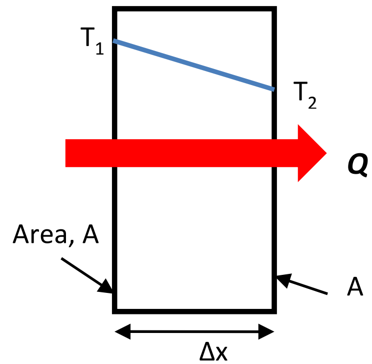
Laminar flow, Re moderate

Turbulent flow, Re high

Thermal conductivity

- Rate of heat conduction is proportional to the temperature difference, but it is inversely proportional to the thickness of the layer

$$\text{Rate of heat transfer} \propto \frac{(\text{surface area})(\text{temperature difference})}{\text{wall thickness}}$$



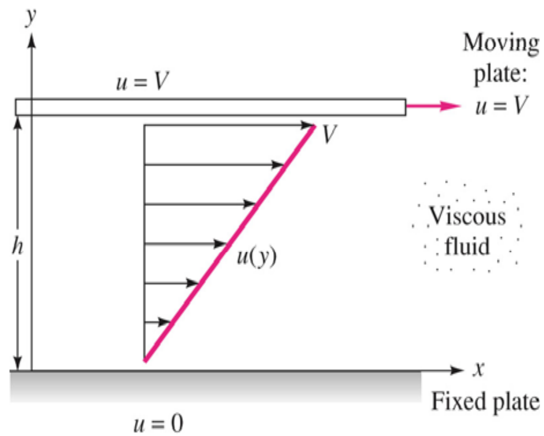
- To make this equality, *k* (*W/m.K*)the thermal conductivity of the material, is introduced.
- This is called the Fourier’s law of heat conduction:

$$q = \frac{Q}{A} = -k\nabla T$$

$$q_x = -k\frac{\partial T}{\partial x}, \quad q_y = -k\frac{\partial T}{\partial y}, \quad q_z = -k\frac{\partial T}{\partial z}$$

SFU Flow between parallel plates

- It is the flow induced between a fixed lower plate and upper plate moving steadily at velocity *V*



- Shear stress is constant throughout the fluid:

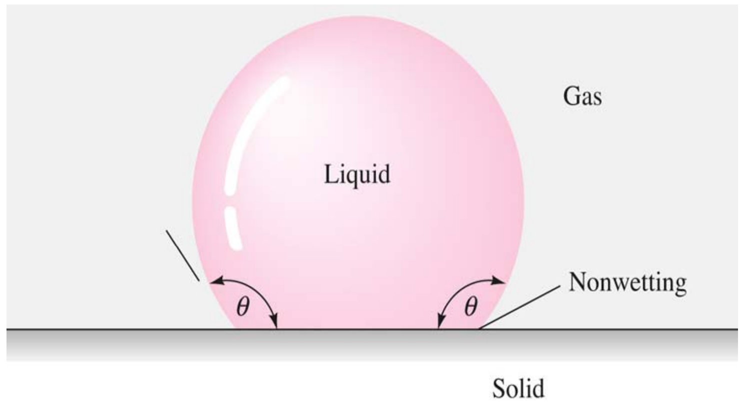
$$\frac{du}{dy} = \frac{\tau}{\mu} = const.$$

- After integration and applying boundary conditions:

$$u = V\frac{y}{h}$$

Surface tension

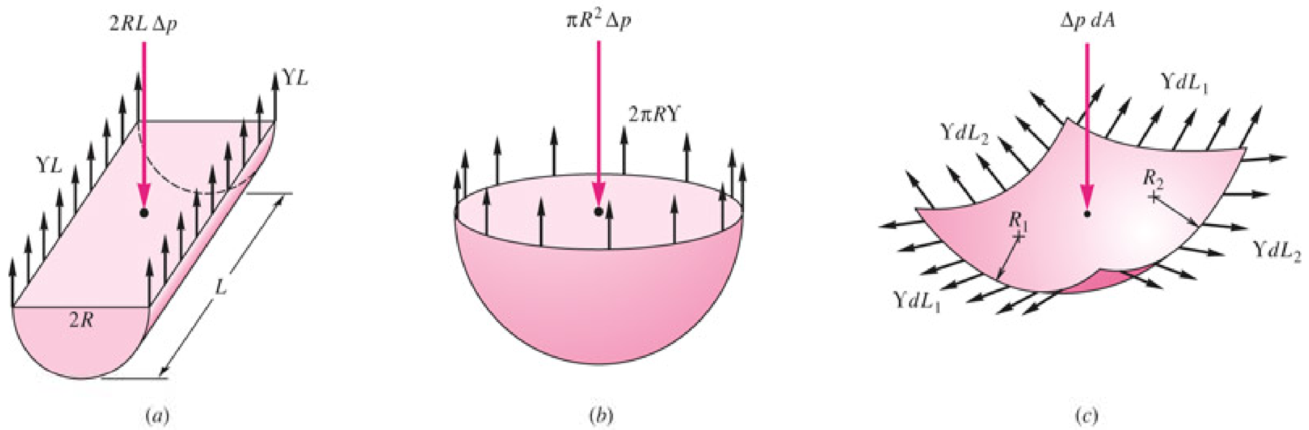
- A liquid, being unable to expand freely, will form an *interface* with a second liquid or gas.



- The cohesive forces between liquid molecules are responsible for the phenomenon known as surface tension.

- Surface tension Y (pronounced upsilon) has the dimension of force per unit length (N/m) or of energy per unit area (J/m^2).
- $Y_{air\text{-}water} = 0.073\ N/m;\ Y_{air\text{-}mercury} = 0.48\ N/m$

Surface tension



- Using a force balance, pressure increase in the interior of a liquid half-cylinder droplet of length L and radius *R* is:

$$2RL\Delta p = 2\Upsilon L \quad or \quad \Delta p = \frac{\Upsilon}{R}$$

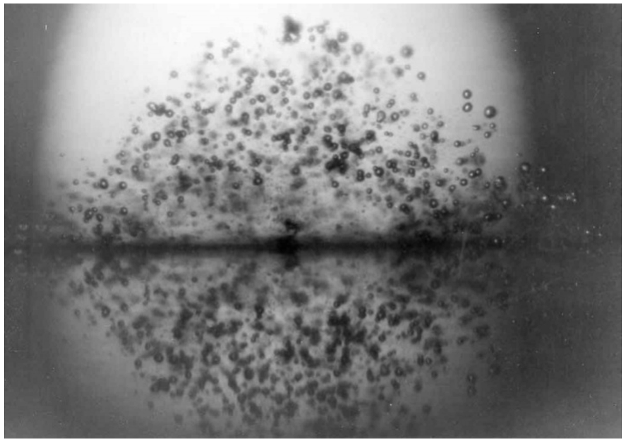
- Contact angle θ appears when a liquid interface intersects with a solid surface.

$$\theta = \begin{cases} < 90° & wetting\ liquid \\ > 90° & nonwetting\ liquid \end{cases}$$

- Water is extremely wetting to a clean glass surface with θ≈0. For a clean mercury-air-glass interface, θ≈130°.

Vapor pressure and cavitation

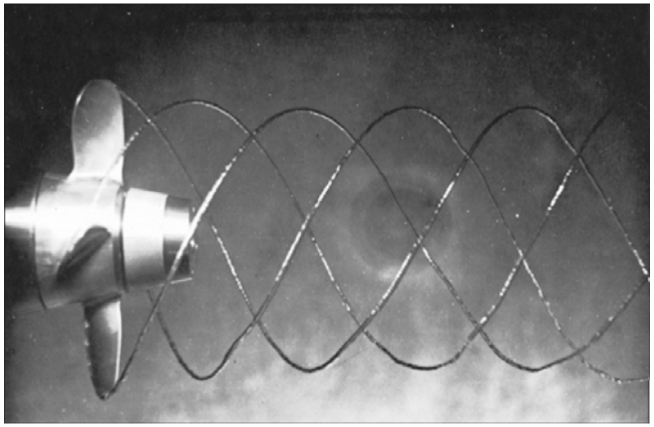
- Vapor pressure: the pressure at which a liquid boils and is in equilibrium with its own vapor.
- When the liquid pressure is dropped below the vapor pressure due to a flow phenomenon, we call the process *cavitation*.



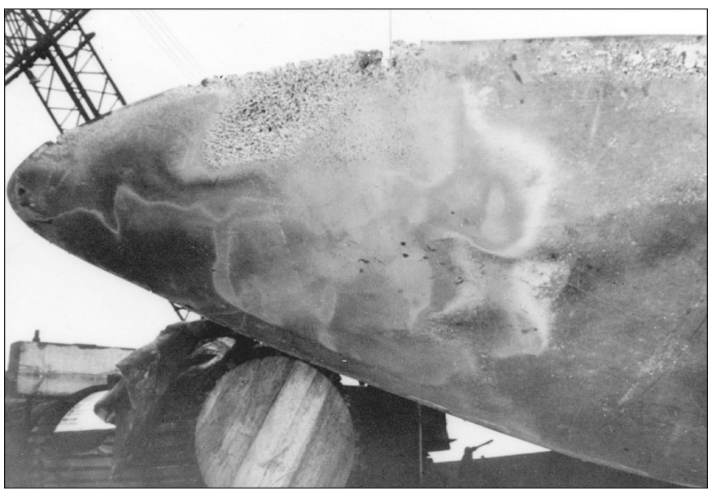
- The dimensionless parameter describing flow-induced boiling is called cavitation number:

$$Ca = \frac{p_a - p_v}{0.5 \rho V^2}$$

Cavitation



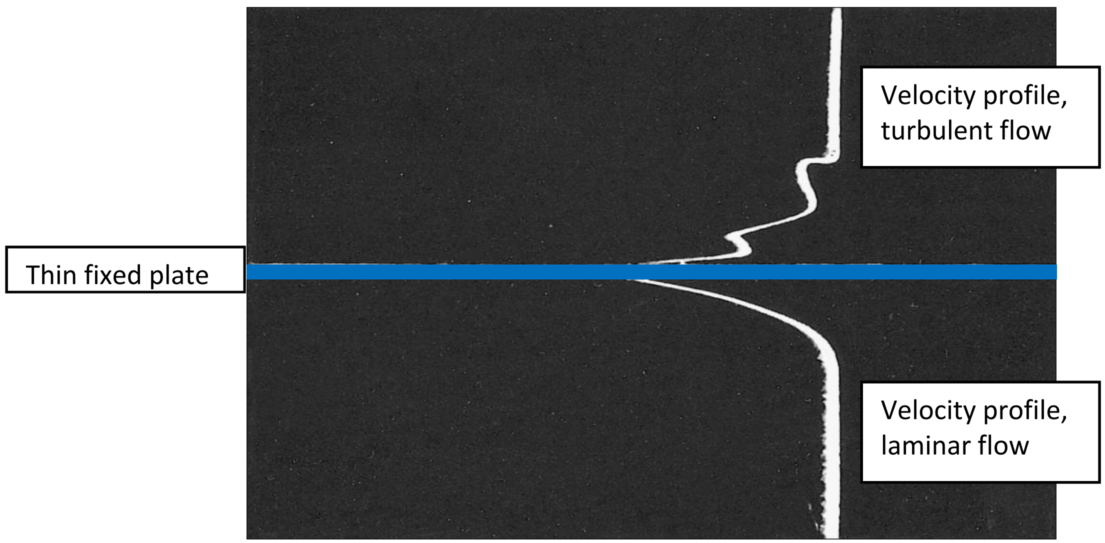

- Bubble formation due to high velocity (flow-induced boiling).




- Damage (erosion) due to cavitation on a marine propeller.

No-slip and no-temp jump

- When a fluid flow is bounded by a surface, molecular interactions cause the fluid in contact with the surface to seek momentum and energy equilibrium with the surface.



$V_{fluid} = V_{wall}$ No-slip flow condition

$T_{fluid} = T_{wall}$ No-temperature jump condition

SFU Speed of sound & compressibility

- the compressibility effects are important at high gas flows due to significant density changes.

- Speed of sound: is the rate of propagation of small disturbance pressure pulses (sound waves) through the fluid:

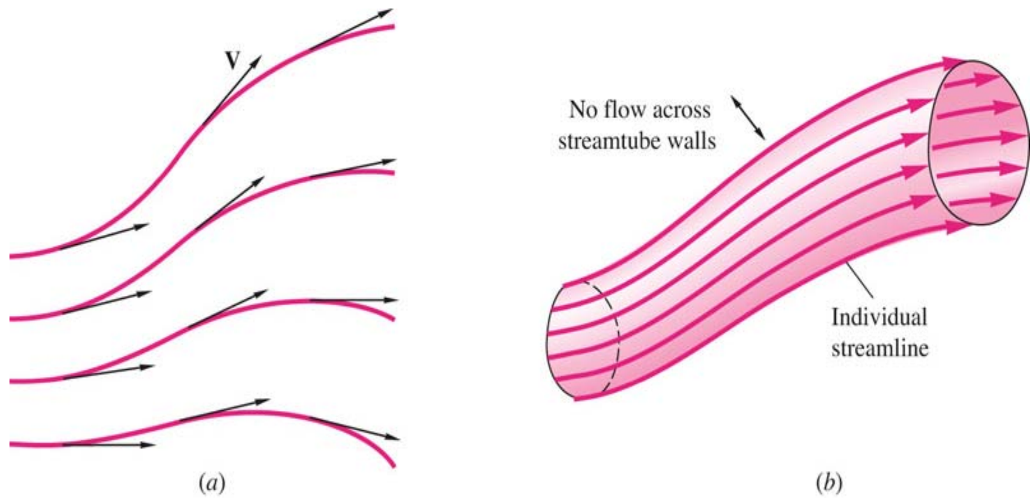
$$a^2 = k\left(\frac{\partial p}{\partial \rho}\right)_T, \qquad k = \frac{c_p}{c_v}$$

- For an ideal gas $a_{ideal\ gas} = \sqrt{kRT}$

- Mach number is the ratio of the flow to the speed of sound $Ma = \frac{V}{a}$

- Compressibility effects are normally neglected for Ma<0.3

Flow pattern



- Streamline: is a line everywhere tangent to the velocity vector at a given instant.
- Pathline: is the actual path traversed by a given fluid particle.
- **Note**: in steady flows, streamlines and pathlines are identical.
- If the elemental arc length *dr* of a streamline is to be parallel to *V*, their respective components must be in proportion:

$$\frac{dx}{u} = \frac{dy}{v} = \frac{dz}{w} = \frac{dr}{V}$$