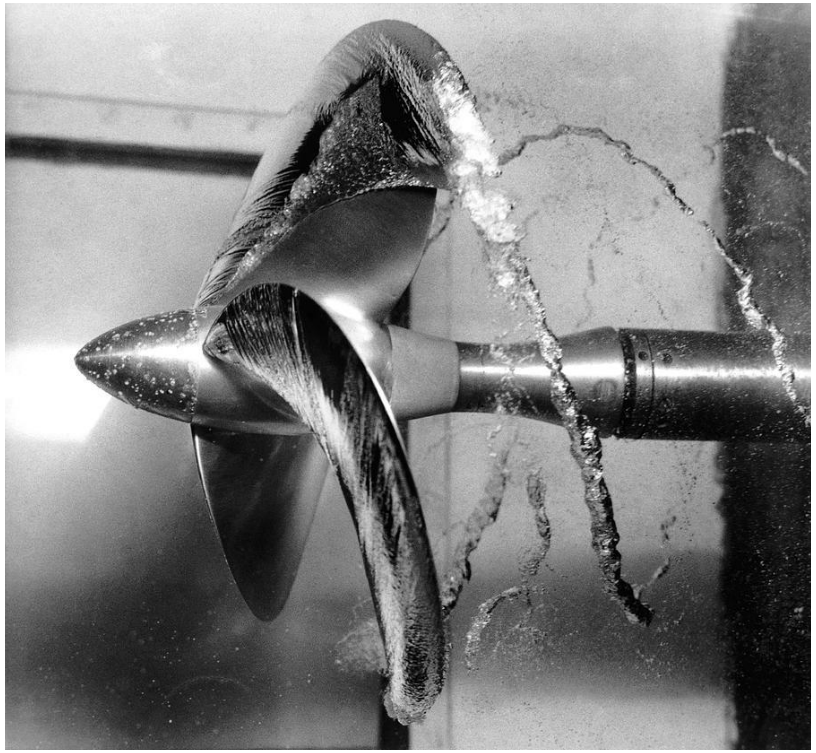
**Florida International University, Department of Civil and Environmental Engineering**

## CWR 3201 Fluid Mechanics, Fall 2018

# Fluid Properties



**Arturo S. Leon, Ph.D., P.E., D.WRE**

# 1.1 INTRODUCTION

**Understanding fluid mechanics is needed for**:

- Biomechanics - To understand the flow of blood and cerebral fluid.
- Meteorology and Ocean Engineering - To understand the motion of air movements and ocean currents.
- Chemical Engineering - To design different kinds of chemical-processing equipment.
- Aeronautical Engineering - To maximize lift, minimize drag on aircraft, and to design fan-jet engines.
- Mechanical Engineering - To design pumps, turbines, internal combustion engines.
- **Civil Engineering** - To design irrigation canals, water distribution systems, flood control systems, etc.

# Motivation for Fluid Properties

## CFD Simulations of Rigid Bodies Falling Under Gravity

https://www.youtube.com/watch?v=LKdii-Y8NQg

## Road Erosion

https://www.youtube.com/watch?v=tacW_yUArPg

# 1.2 DIMENSIONS, UNITS, AND PHYSICAL QUANTITIES

**Fundamental Dimensions** - Nine quantities that can express all other quantities.

**Table 1.1** Fundamental Dimensions and Their Units

| *Quantity* | *Dimensions* | *SI units* | | *English units* | |
|---|---|---|---|---|---|
| Length $\ell$ | $L$ | meter | m | foot | ft |
| Mass $m$ | $M$ | kilogram | kg | slug | slug |
| Time $t$ | $T$ | second | s | second | sec |
| Electric current $i$ | | ampere | A | ampere | A |
| Temperature $T$ | $\Theta$ | kelvin | K | Rankine | °R |
| Amount of substance | $M$ | kg-mole | kmol | lb-mole | lbmol |
| Luminous intensity | | candela | cd | candela | cd |
| Plane angle | | radian | rad | radian | rad |
| Solid angle | | steradian | sr | steradian | sr |

# 1.2 DIMENSIONS, UNITS, AND PHYSICAL QUANTITIES

In general, for the study of mechanics of fluids, **four fundamental dimensions** are used:

Length (L), mass (M), time (T) and temperature ($\Theta$) or

Length (L), force (F), time (T) and temperature ($\Theta$)

**Example:** Dimensions of *Force* in MLT

**There are two primary systems of units:**

- English units
- Système International units (SI)

**Derived Quantities** - Combinations of fundamental quantities to form different parameters.

**Table 1.2** Derived Units

| *Quantity* | *Dimensions* | *SI units* | *English units* |
|---|---|---|---|
| Area $A$ | $L^2$ | $m^2$ | $ft^2$ |
| Volume $\mathcal{V}$ | $L^3$ | $m^3$<br>L (liter) | $ft^3$ |
| Velocity $V$ | $L/T$ | m/s | ft/sec |
| Acceleration $a$ | $L/T^2$ | $m/s^2$ | $ft/sec^2$ |
| Angular velocity $\omega$ | $T^{-1}$ | rad/s | rad/sec |
| Force $F$ | $ML/T^2$ | $kg \cdot m/s^2$<br>N (newton) | $slug\text{-}ft/sec^2$<br>lb (pound) |
| Density $\rho$ | $M/L^3$ | $kg/m^3$ | $slug/ft^3$ |
| Specific weight $\gamma$ | $M/L^2T^2$ | $N/m^3$ | $lb/ft^3$ |
| Frequency $f$ | $T^{-1}$ | $s^{-1}$ | $sec^{-1}$ |
| Pressure $p$ | $M/LT^2$ | $N/m^2$<br>Pa (pascal) | $lb/ft^2$<br>(psf) |
| Stress $\tau$ | $M/LT^2$ | $N/m^2$<br>Pa (pascal) | $lb/ft^2$<br>(psf) |
| Surface tension $\sigma$ | $M/T^2$ | N/m | lb/ft |
| Work $W$ | $ML^2/T^2$ | $N \cdot m$<br>J (joule) | ft-lb |
| Energy $E$ | $ML^2/T^2$ | $N \cdot m$<br>J (joule) | ft-lb |
| Heat rate $\dot{Q}$ | $ML^2/T^3$ | J/s | Btu/sec |
| Torque $T$ | $ML^2/T^2$ | $N \cdot m$ | ft-lb |
| Power $P$<br>$\dot{W}$ | $ML^2/T^3$ | J/s<br>W (watt) | ft-lb/sec |
| Viscosity $\mu$ | $M/LT$ | $N \cdot s/m^2$ | $lb\text{-}sec/ft^2$ |
| Mass flux $\dot{m}$ | $M/T$ | kg/s | slug/sec |
| Flow rate $Q$ | $L^3/T$ | $m^3/s$ | $ft^3/sec$ |
| Specific heat $c$ | $L^2/T^2\Theta$ | $J/kg \cdot K$ | Btu/slug-°R |
| Conductivity $K$ | $ML/T^3\Theta$ | $W/m \cdot K$ | lb/sec-°R |

**Table 1.3** SI Prefixes

| *Multiplication factor* | *Prefix* | *Symbol* |
|---|---|---|
| $10^{12}$ | tera | T |
| $10^{9}$ | giga | G |
| $10^{6}$ | mega | M |
| $10^{3}$ | kilo | k |
| $10^{-2}$ | centi[a] | c |
| $10^{-3}$ | milli | m |
| $10^{-6}$ | micro | μ |
| $10^{-9}$ | nano | n |
| $10^{-12}$ | pico | p |

[a]Permissible if used alone as cm, $cm^2$, or $cm^3$.

**Example 1.1 (textbook):** A mass of 100 kg is acted on by a 400-N force acting vertically upward and a 600-N force acting upward at a 45º angle. Calculate the vertical component of the acceleration. The rollers are frictionless.

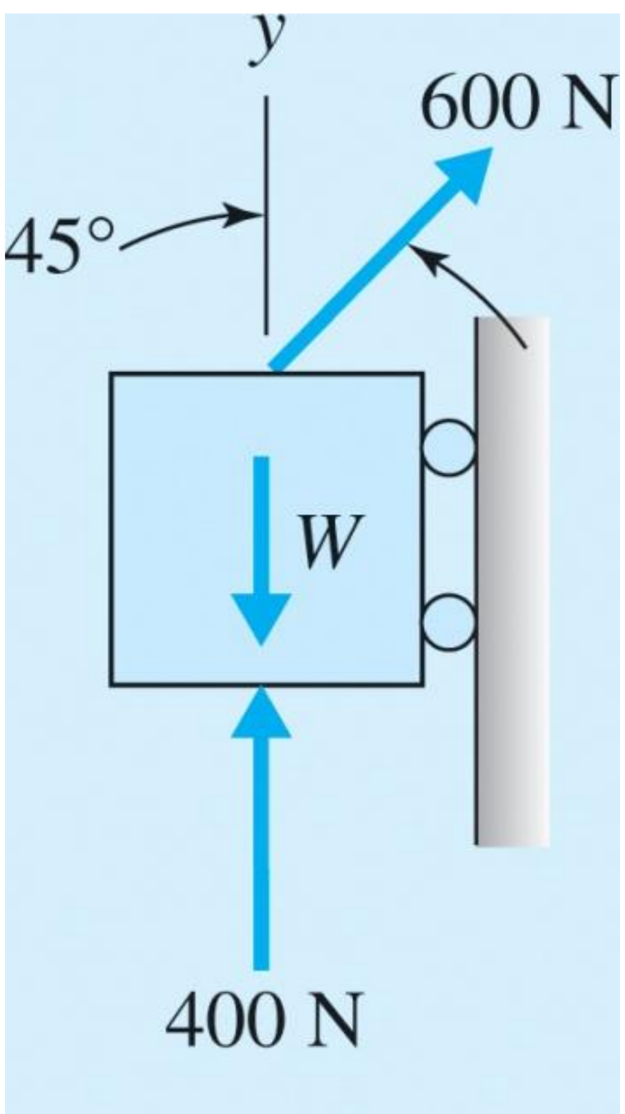



**Fig. E1.1**

# 1.3 CONTINUUM VIEW OF GASES AND LIQUIDS

- Substances can be both liquids or gases.
  - **Liquids** - matter in which molecules are relatively free to change their positions with respect to each other. The molecules are restricted by cohesive forces so as to maintain a relatively fixed volume.
  - **Gas** – matter in which molecules are unrestricted by cohesive forces. Gas has neither definite shape nor volume.

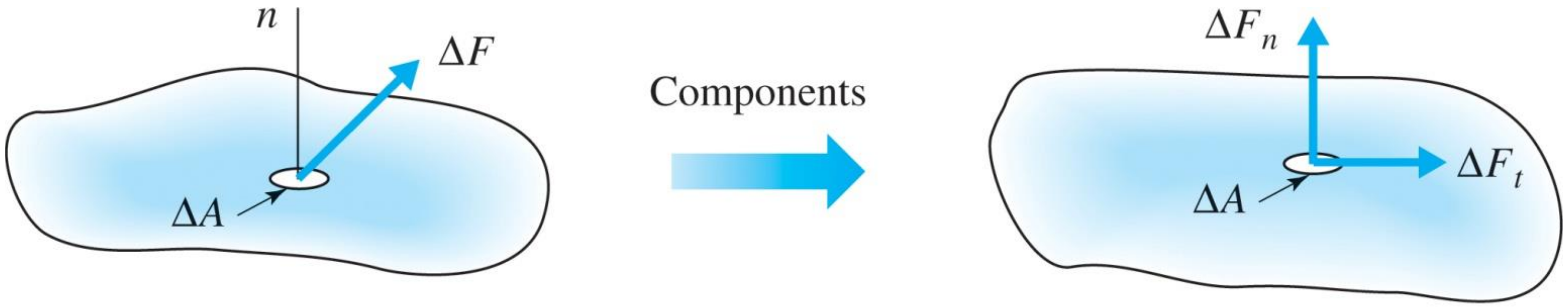



**Fig. 1.1** Normal and tangential components of a force.

A force ΔF that acts on an area ΔA can be broken into tangential ($F_t$) and normal ($F_n$) components.

**Stress** - Force divided by the area upon which it acts.

# 1.3 CONTINUUM VIEW OF GASES AND LIQUIDS

- **Stress Vector** - The force vector divided by the area.
- **Normal Stress** - Normal component of force divided by the area.
- **Shear Stress ($\tau$)** - Tangential force divided by the area. (defined as shown below)

# 1.3 CONTINUUM VIEW OF GASES AND LIQUIDS

- Assume that fluids act as a continuum:
  - A continuous distribution of a liquid or gas throughout a region of interest

- Density is used to find out if the continuum assumption is appropriate.
  - $\Delta m$: Incremental mass $\Delta V$: Incremental volume

- **Standard Atmospheric Conditions**
  - Pressure: 101.3 kPa (14.7 psi, 1.013 bars, 760 mm Hg)
  - Temperature: 15°C (59°F)
  - Density of air: 1.23 kg/$m^3$ (0.00238 slug/$ft^3$)
  - Density of water: 1000 kg/$m^3$ (1.94 slug/$ft^3$)

# 1.4 PRESSURE AND TEMPERATURE SCALES

- The pressure, p, can be defined as:

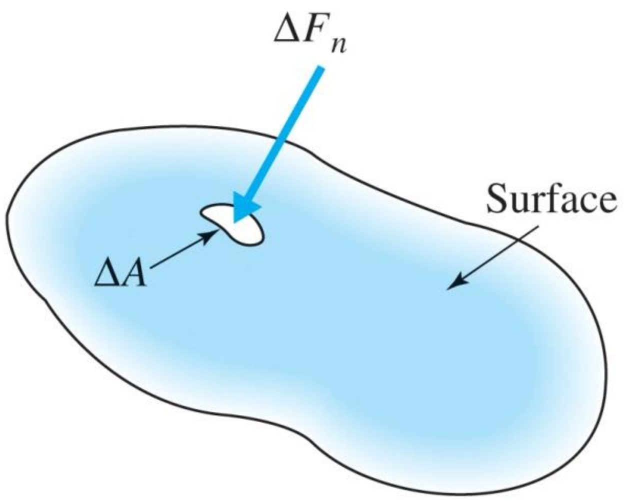



**Fig. 1.3** Definition of pressure.

**$\Delta F_n$**: Incremental normal compressive force

**ΔA:** Incremental area

**Units:** $N/m^2$ or Pa

- **Absolute Pressure**: Zero is reached for an ideal vacuum.
- **Gage Pressure**: Pressure relative to the local atmospheric pressure.

## 1.4 PRESSURE AND TEMPERATURE SCALES

- Temperature scales (Celsius and Fahrenheit scales)

**Celsius to Kelvin**

**Fahrenheit to Rankine**

| | °C | K | °F | °R |
|---|---|---|---|---|
| Steam point | 100° | 373 | 212° | 672° |
| Ice point | 0° | 273 | 32° | 492° |
| Special point | –18° | 255 | 0° | 460° |
| Zero absolute temperature | | | | |

**Fig. 1.5** Temperature scales.

# 1.5 FLUID PROPERTIES

- **Specific Weight, $\gamma$**: Weight per unit volume
  - **Units**: $N/m^3$ or $lb/ft^3$

*g*: Local gravity

- **Specific Gravity, *S***: Ratio of density of a substance to the density of water at 4°C.
  - **Units**: Dimensionless

**TABLE 1.4** Density, Specific Weight, and Specific Gravity of Air and Water at Standard Conditions

| | *Density* $\rho$ | | *Specific weight* $\gamma$ | | |
|---|---|---|---|---|---|
| | $kg/m^3$ | $slug/ft^3$ | $N/m^3$ | $lb/ft^3$ | *Specific gravity S* |
| Air | 1.23 | 0.0024 | 12.1 | 0.077 | 0.00123 |
| Water | 1000 | 1.94 | 9810 | 62.4 | 1 |

# 1.5 FLUID PROPERTIES

- **Viscosity, $\mu$**: Measure of the resistance of a fluid to gradual deformations by shear stress.
  - Accounts for energy losses in the transport of fluids in ducts or pipes
  - Plays a role in the generation of turbulence

- **Units:** N.s/m$^2$ or lb-s/ft$^2$

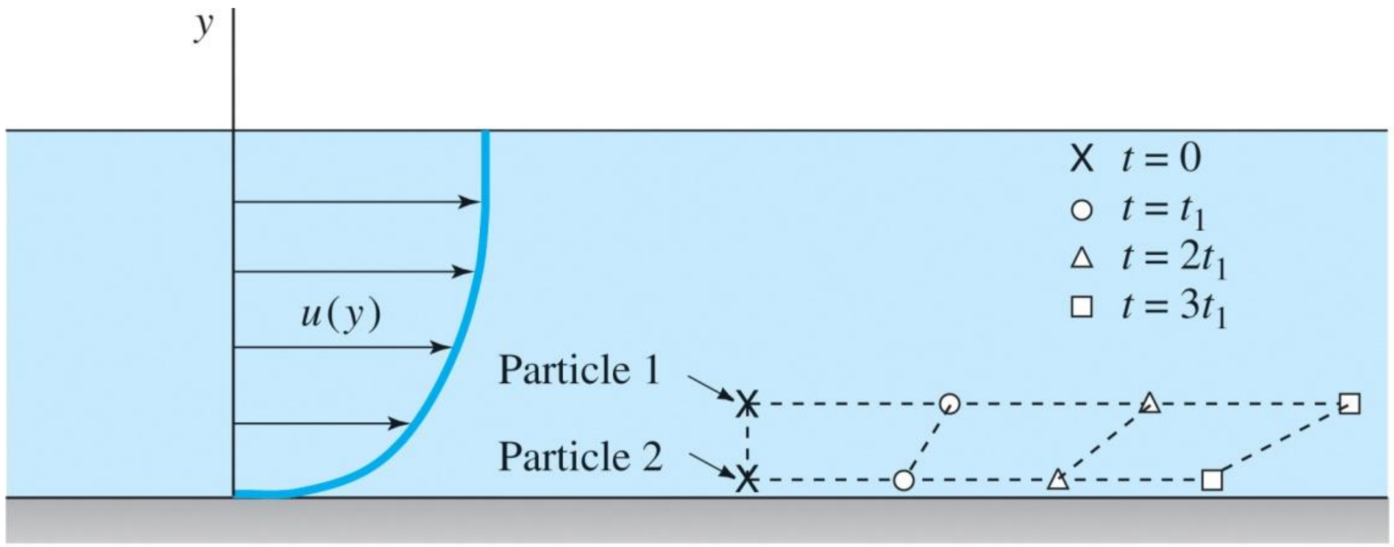



**Fig. 1.6** Relative movement of two fluid particles in the presence of shear stresses.

# 1.5 FLUID PROPERTIES

- **Newtonian fluid**: A fluid in which the shear stress is directly proportional to the velocity gradient. e.g., Air, water, and oil
- **Non-Newtonian fluid:** A fluid in which the shear stress is NOT directly proportional to the velocity gradient. e.g., slurries

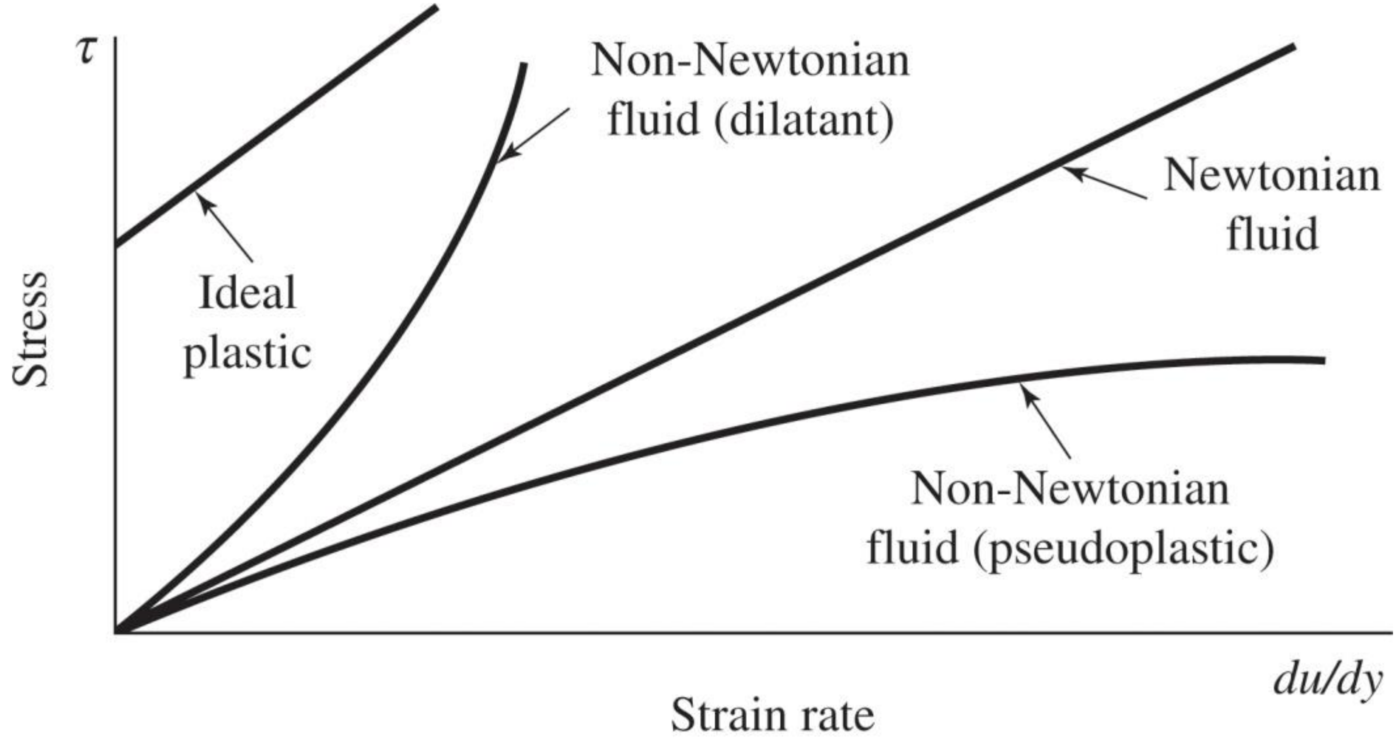
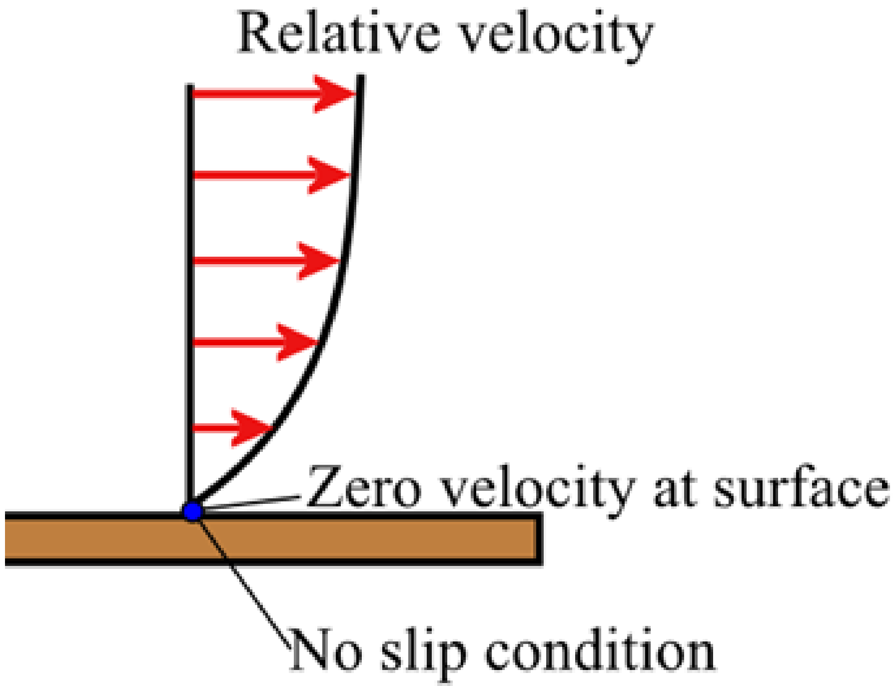



**Fig. 1.8** Newtonian and non-Newtonian fluids.

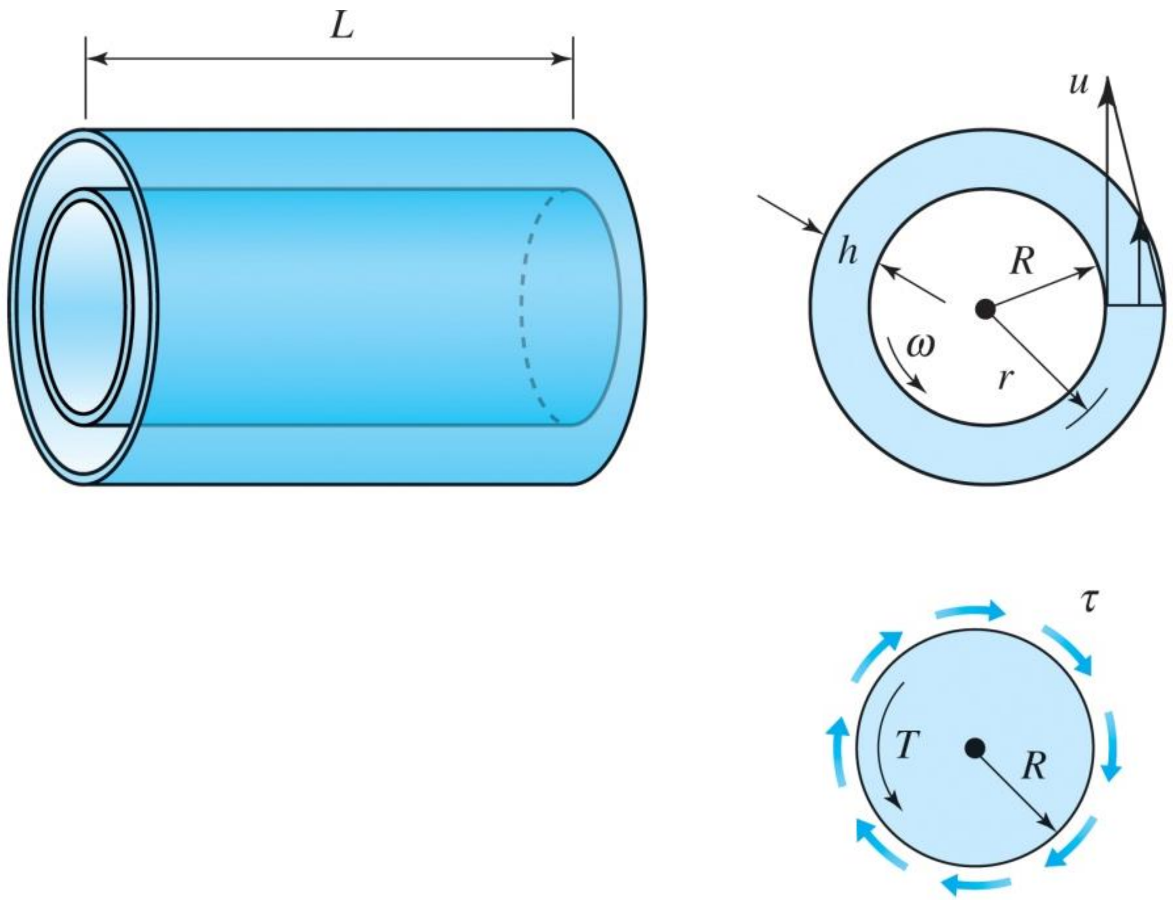
# 1.5 FLUID PROPERTIES

- **No-slip Condition**: Causes fluid to adhere to the surface (due to viscosity)




- kinematic viscosity = dynamic viscosity/density
- Units of kinematic viscosity: $m^2/s$ or $ft^2/s$

**Example:** **P.1.45**. For two 0.2-m long rotating concentric cylinders, the velocity distribution is given by $u(r) = 0.4/r - 1000r$ m/s, where $r$ is in m. If the diameters of the cylinders are 2 cm and 4 cm, respectively, calculate the fluid viscosity if the torque on the inner cylinder is measured to be 0.0026 N-m.



### 1.5.3 Compressibility

- Can be described using the **Bulk modulus of elasticity, *B***.
  - This is the **ratio of the change in pressure to relative change in density**.
  - Same units as pressure.
- For gases:
  - Significant changes in density (~4%) - Compressible.
  - Small density changes (under 3%) - Incompressible.

- The speed of sound in a liquid can be found using the Bulk modulus of elasticity and density, as shown above.

**Example:** **P.1.54**. Two engineers wish to estimate the distance across a lake. One pounds two rocks together under water on one side of the lake and the other submerges his head and hears a small sound 0.62 s later, as indicated by a very accurate stopwatch. What is the distance between the two engineers?

# 1.5.4 Surface Tension

**Video:** https://www.khanacademy.org/science/physics/fluids/fluid-dynamics/v/surface-tension-and-adhesion

- Results from the attractive forces between molecules. Hence seen only in liquids at an interface (liquid-gas).
- Forces between molecules in a liquid bulk are equal in all directions.
  - No net force is exerted on them.
- At an interface, the molecules exert a force that has a resultant force.
  - Holds a drop of water on a rod and limits its size.

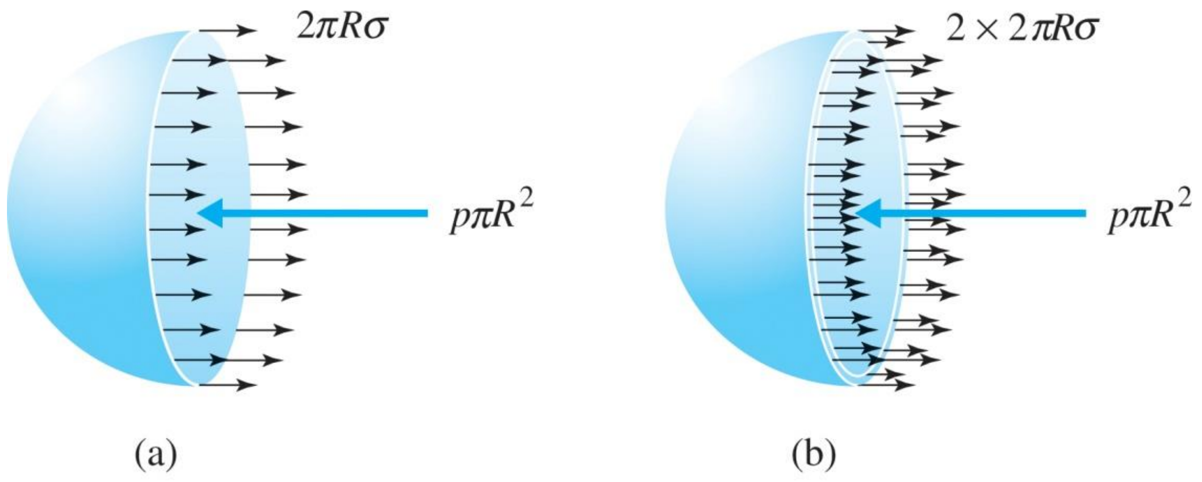



**Fig. 1.9** Internal forces in (a) a droplet and (b) a bubble.

# 1.5.4 Surface Tension

- Unit: Force per unit length, N/m or lb/ft.
- Force results from the length (of fluid in contact with a solid) multiplied by the surface tension.
  - A **droplet** has **one surface**.
  - A **bubble** is a thin film of liquid with an **inside** and an outside surface.

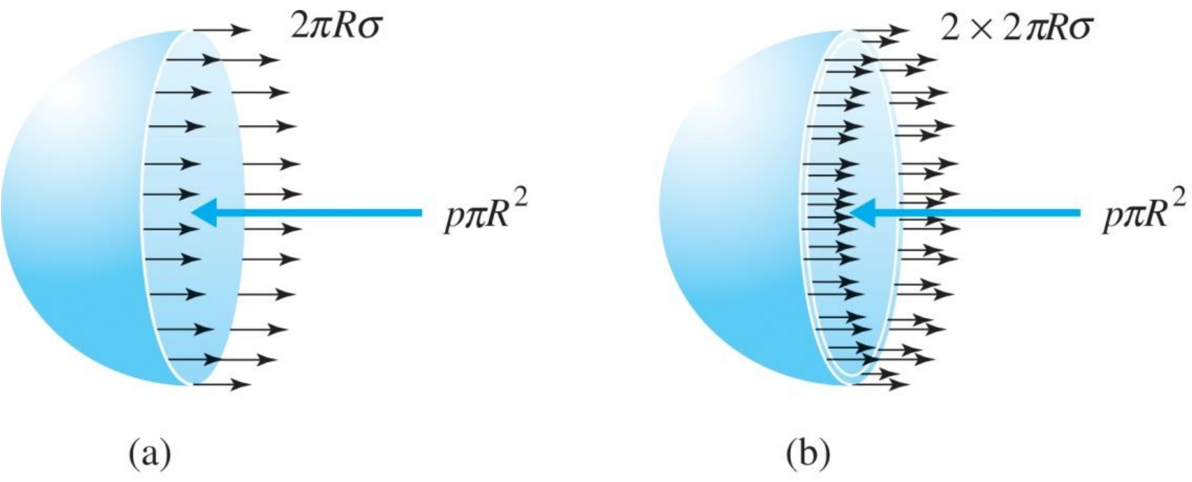



**Fig. 1.9** Internal forces in (a) a droplet and (b) a bubble.

Pressure in the droplet balances the surface tension around the circumference.

Pressure in the bubble is balanced by the surface tension forces on the two circumferences.

# 1.5 FLUID PROPERTIES

## 1.5.4 Surface Tension

- As seen before, **the internal pressure in a bubble is twice as large as that in a droplet** of a similar size.

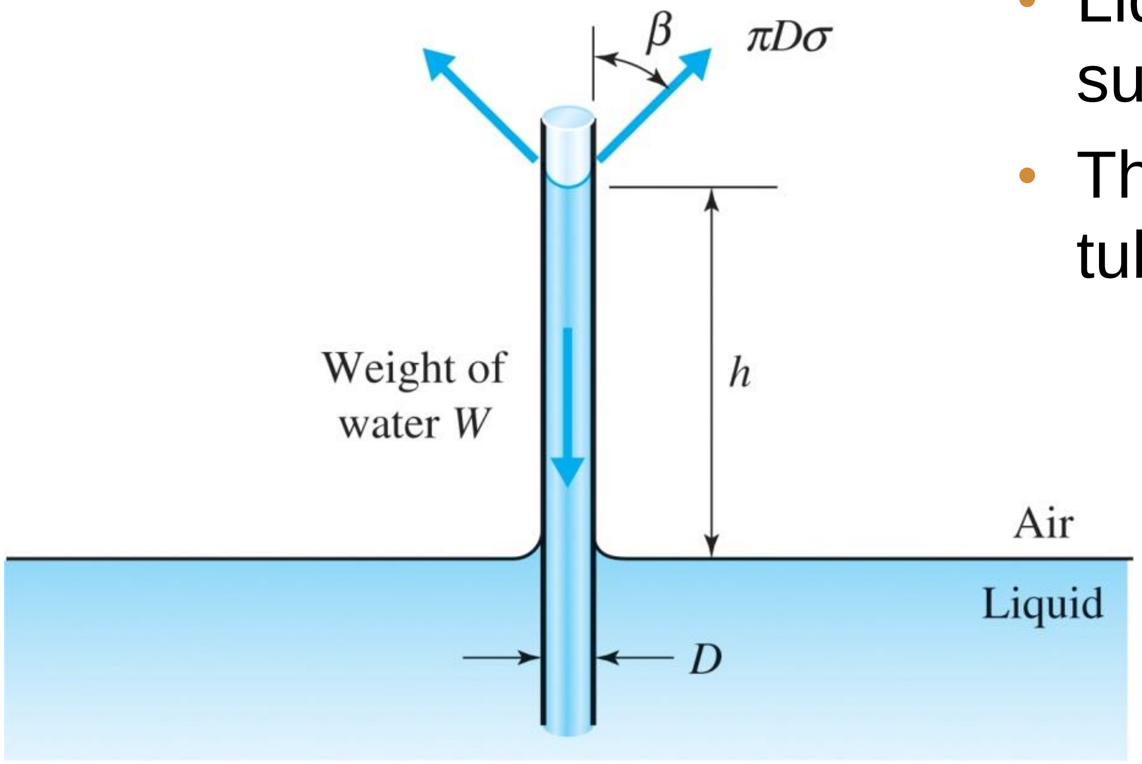



**Fig. 1.10** Rise in a capillary tube.

- Liquid rises in a glass capillary tube due to surface tension.
- The liquid makes a contact angle β with a glass tube.
  - **For most liquids (and water) this angle β is zero**.
  - Mercury has an angle greater than 90°.

# 1.5 FLUID PROPERTIES

## 1.5.4 Surface Tension

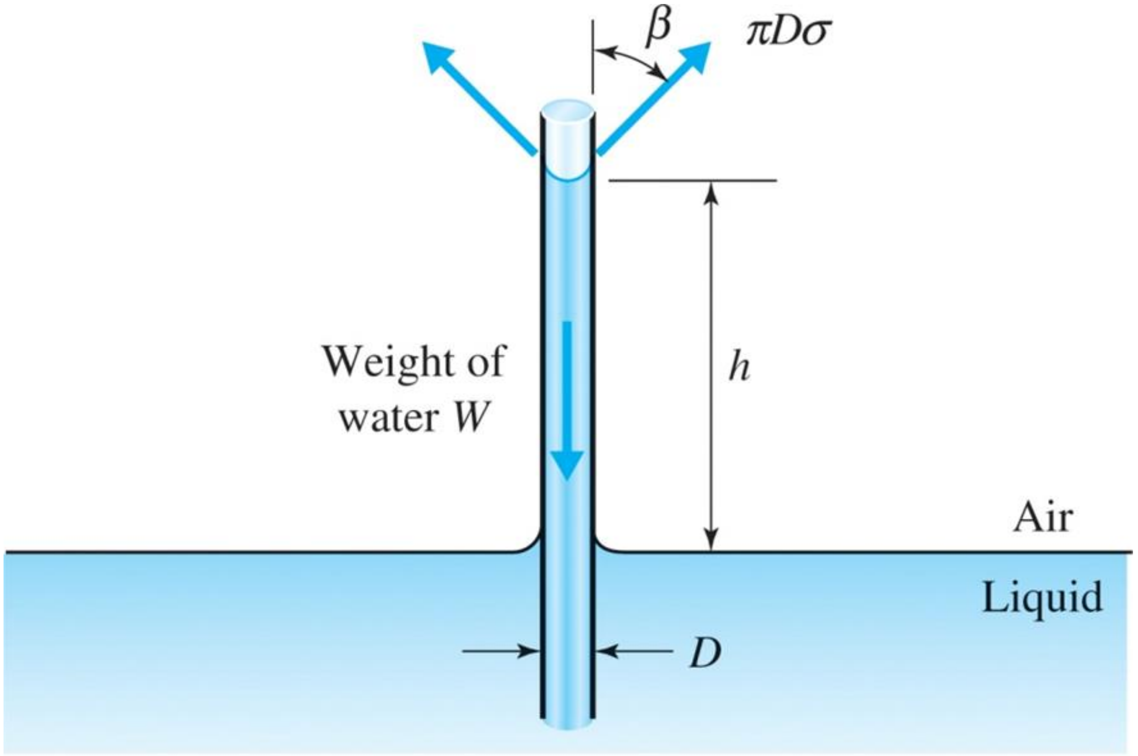



**Fig. 1.10** Rise in a capillary tube.

- *h*: Capillary rise
- *D*: Tube diameter
- *σ*: Surface tension

**Example:** **P.1.62**. Mercury makes an angle of 130º ($\beta$ in Fig. 1.10) when in contact with clean glass. What distance will mercury depress in a vertical 0.8-in diameter glass tube? Use $\sigma$ = 0.032 lb/ft.

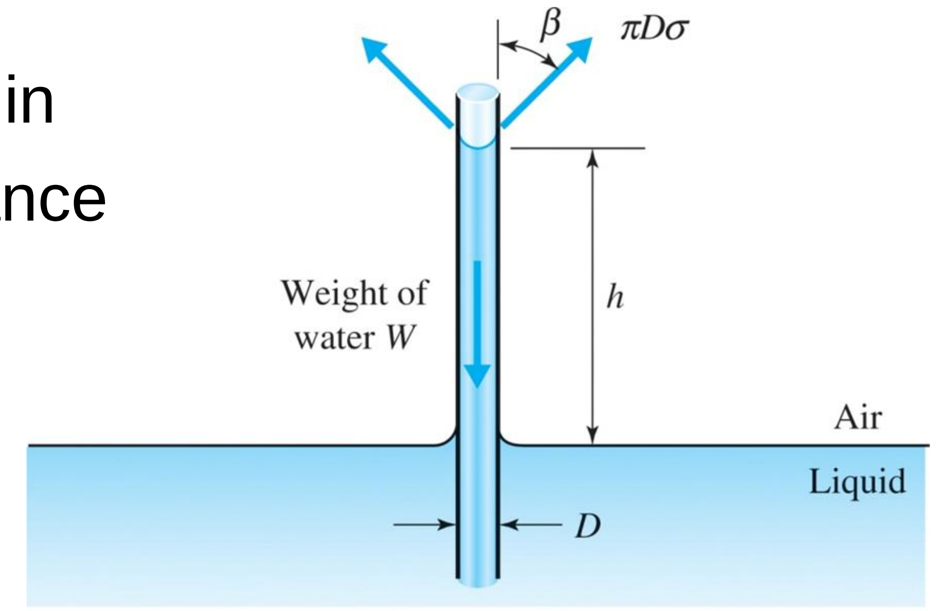
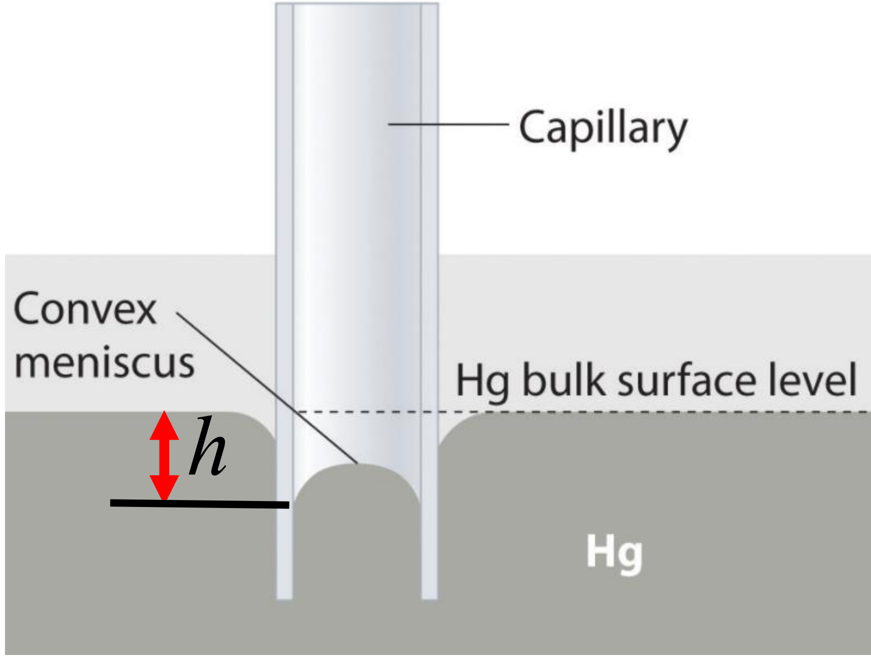



**Fig. 1.10** Rise in a capillary tube.



## Additional Examples:

**P.1.20**. Determine the units on *c*, *k* and *f(t)* in

$m\frac{d^2y}{dt^2} + c\frac{dy}{dt} + ky = f(t)$ if *m* is in Kilograms, *y* is in meters, and *t* is in seconds

**P.1.26**. A particular body weighs 60 lb on earth. Calculate its weight on the moon, where $g \approx 5.4$ ft/s$^2$.

**P.1.49**. Calculate the torque needed to rotate the cone shown in Figure P1.49 at 2000 rpm if SAE-30 oil at 40ºC fills the gap. Assume a linear velocity profile between the cone and the fixed wall.

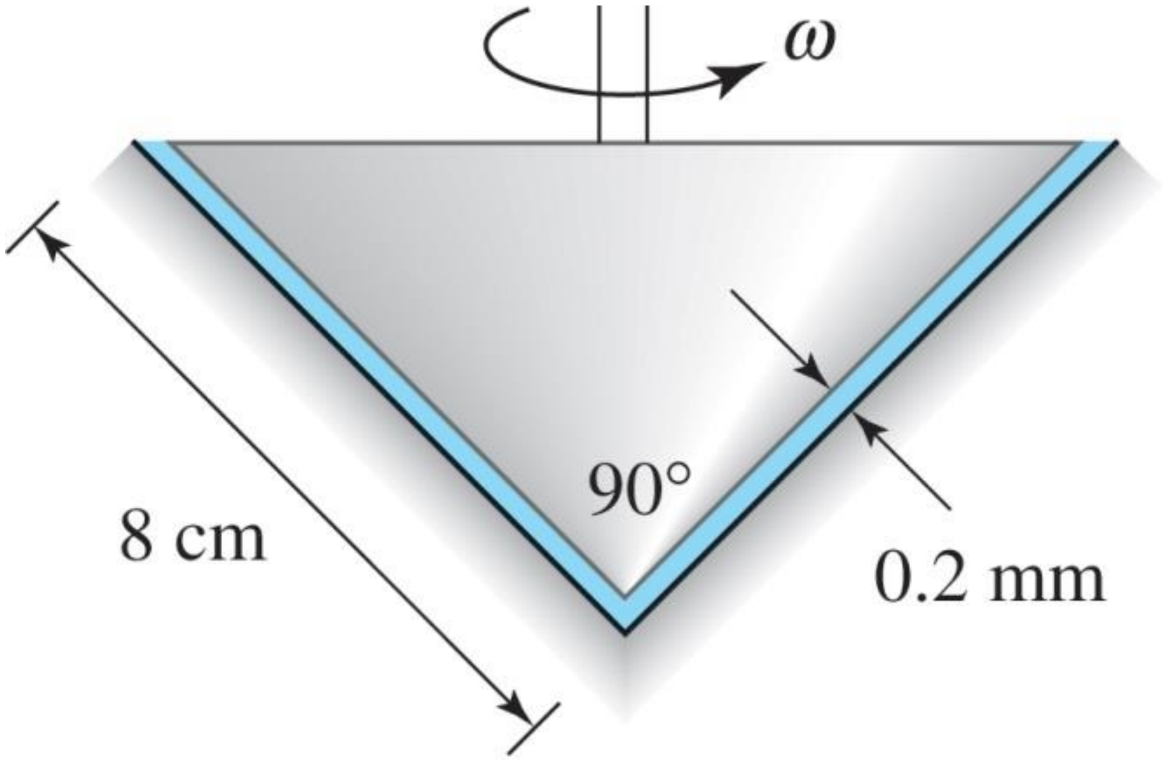



**Fig. P1.49**

**P.1.66**. Find an expression for the maximum vertical force *F* needed to lift a thin wire ring of diameter *D* slowly from a liquid with surface tension $\sigma$.

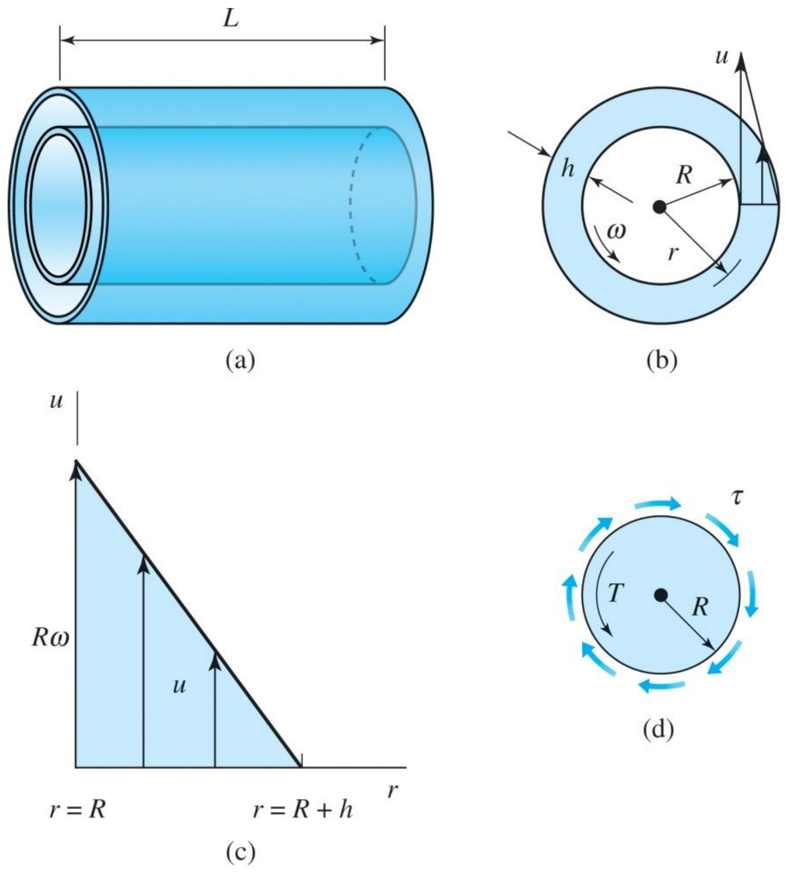



**Fig. 1.7** Fluid being sheared between cylinders with a small gap: (a) the two cylinders; (b) rotating inner cylinder; (c) velocity distribution; (d) the inner cylinder. The outer cylinder is fixed and the inner cylinder is rotating.

# Example 1.4

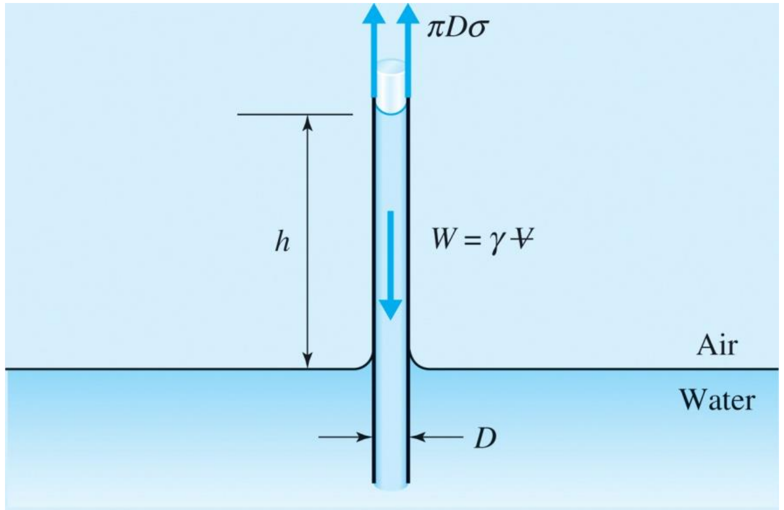



**Fig. E1.4**

**Fig. 1.11** Cooking food in boiling water takes a longer amount of time at a high altitude. It would take longer to boil these eggs in Denver than in New York City. (Thomas Firak Photography/FoodPix/Getty Images)

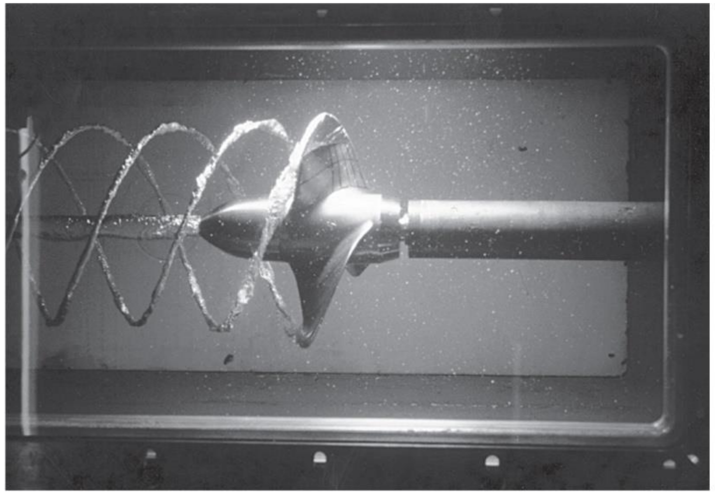


**Fig. 1.12** A photograph of a cavitating propeller inside MIT's water tunnel.
(Courtesy of Prof. S. A. Kinnas, Ocean Engineering Group, University of Texas - Austin.)

Example 1.7

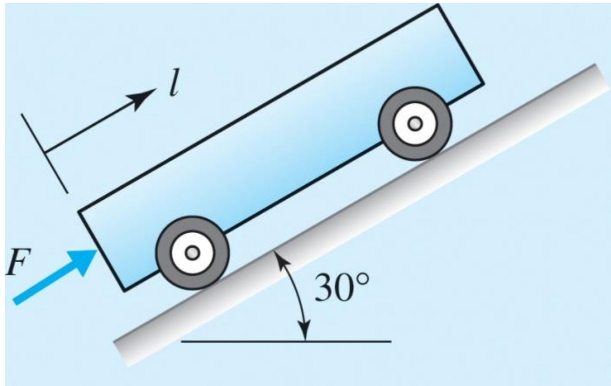



Fig. E1.7

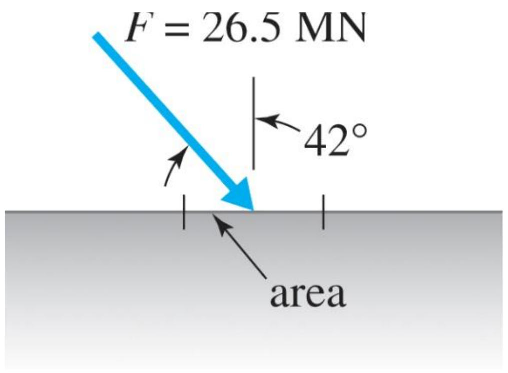



**Fig. P1.33**

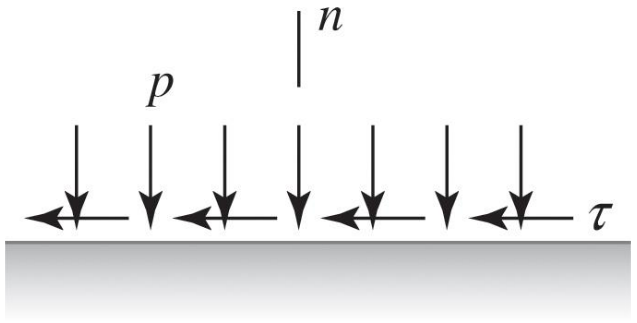



Fig. P1.34

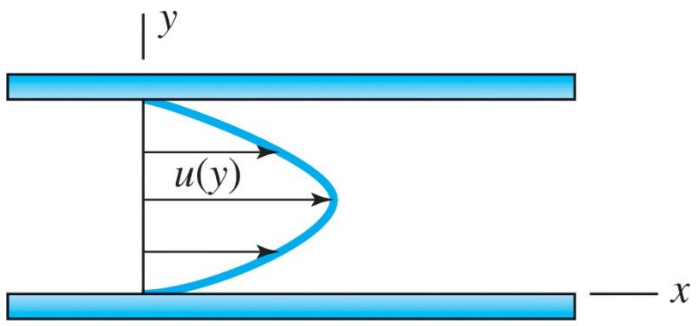



**Fig. P1.42**

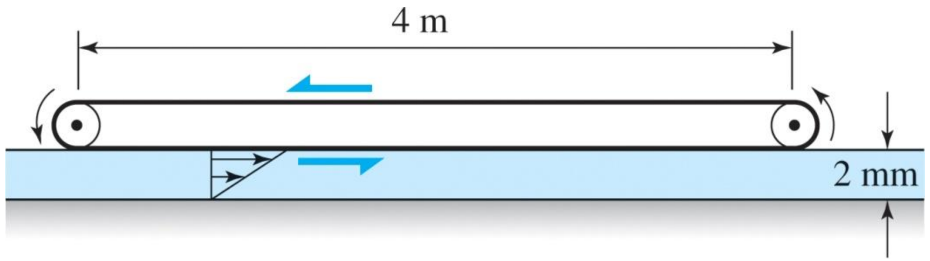



Fig. P1.47

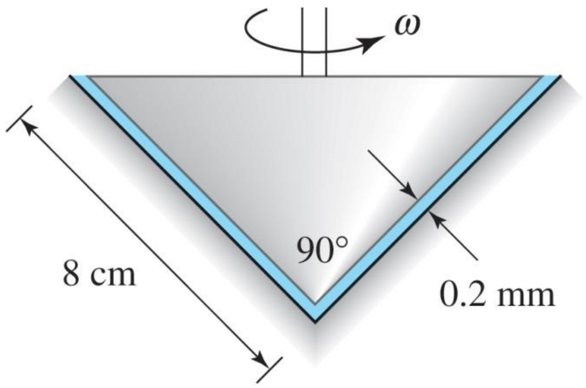



**Fig. P1.49**

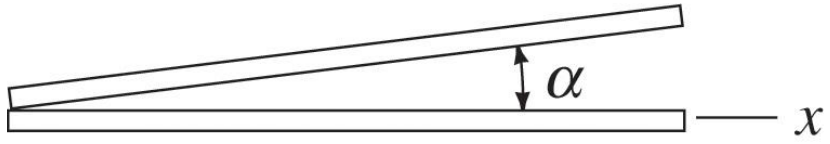



Fig. P1.67

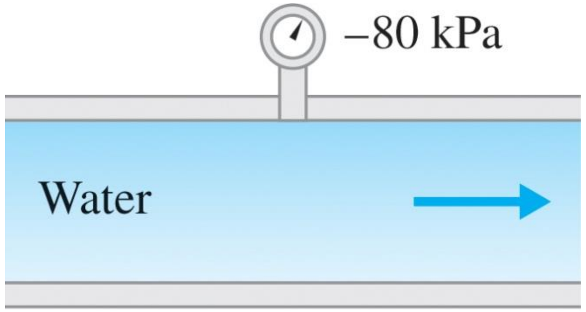



Fig. P1.68

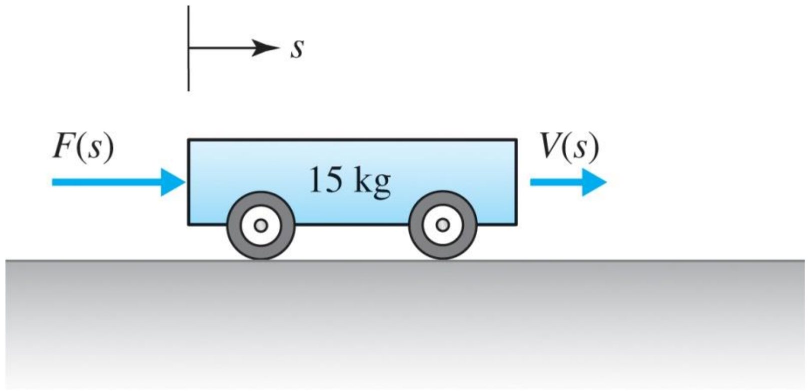



Fig. P1.80

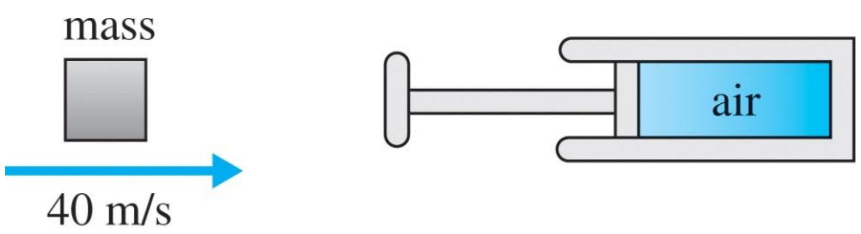



Fig. P1.81

# Typical components of a pipe system

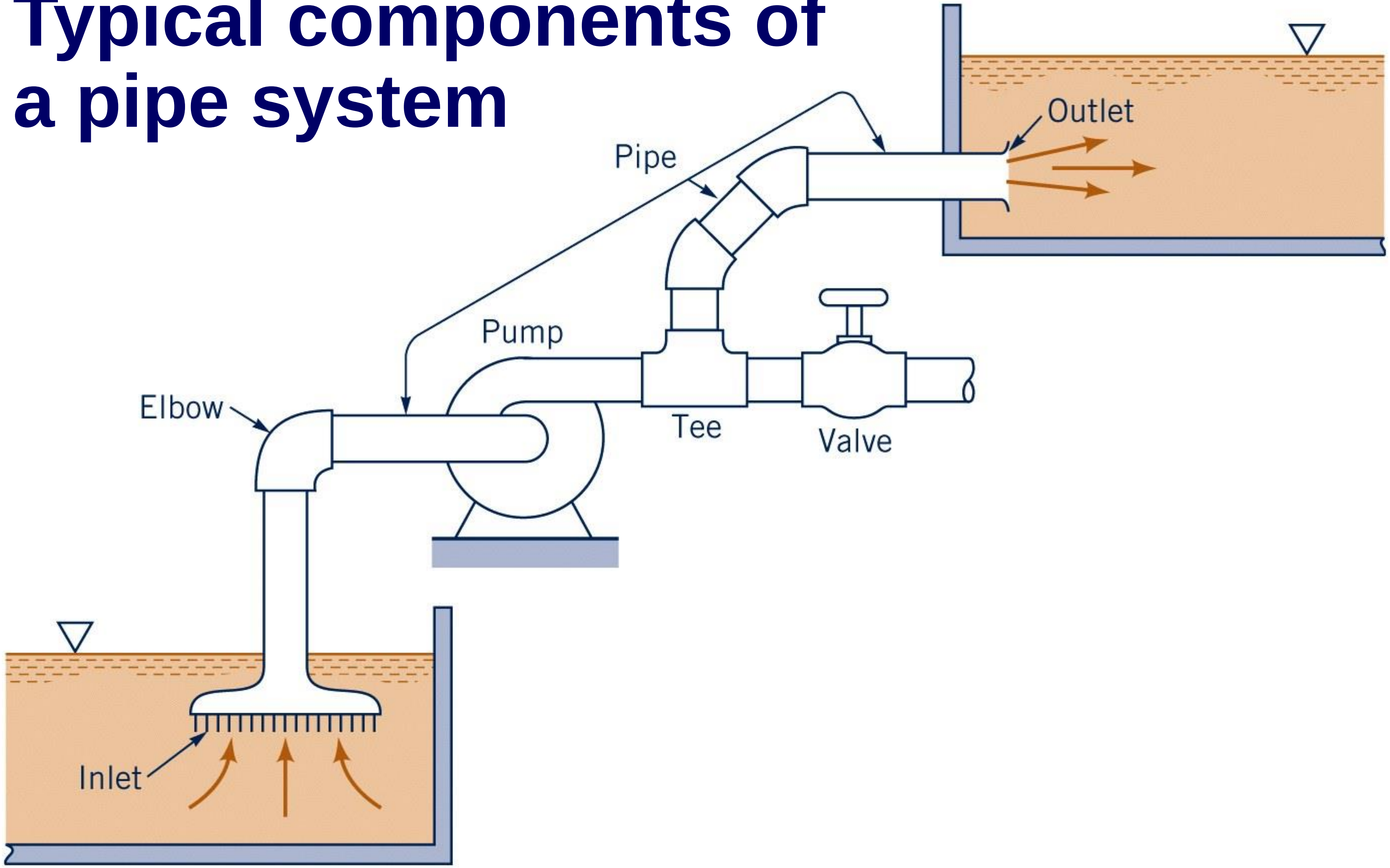



Figure 8.1

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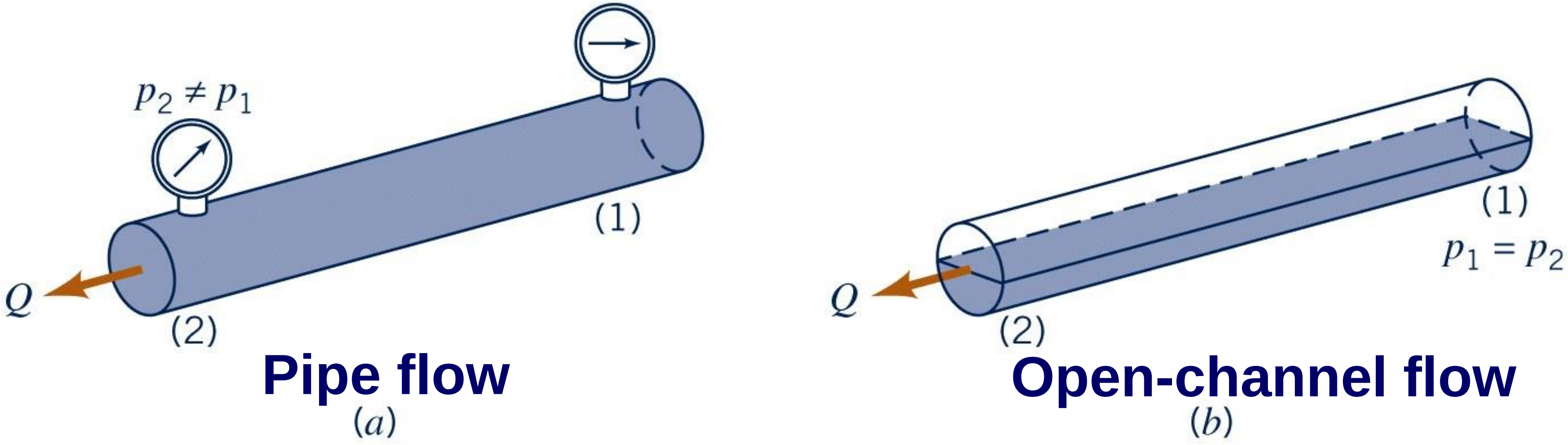
# General Characteristics of pipe flow




**Pipe flow**

**Open-channel flow**

Figure 8.2
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# Laminar or Turbulent Flow?

(http://www.youtube.com/watch?v=WG-YCpAGgQQ)

# Laminar or Turbulent Flow?

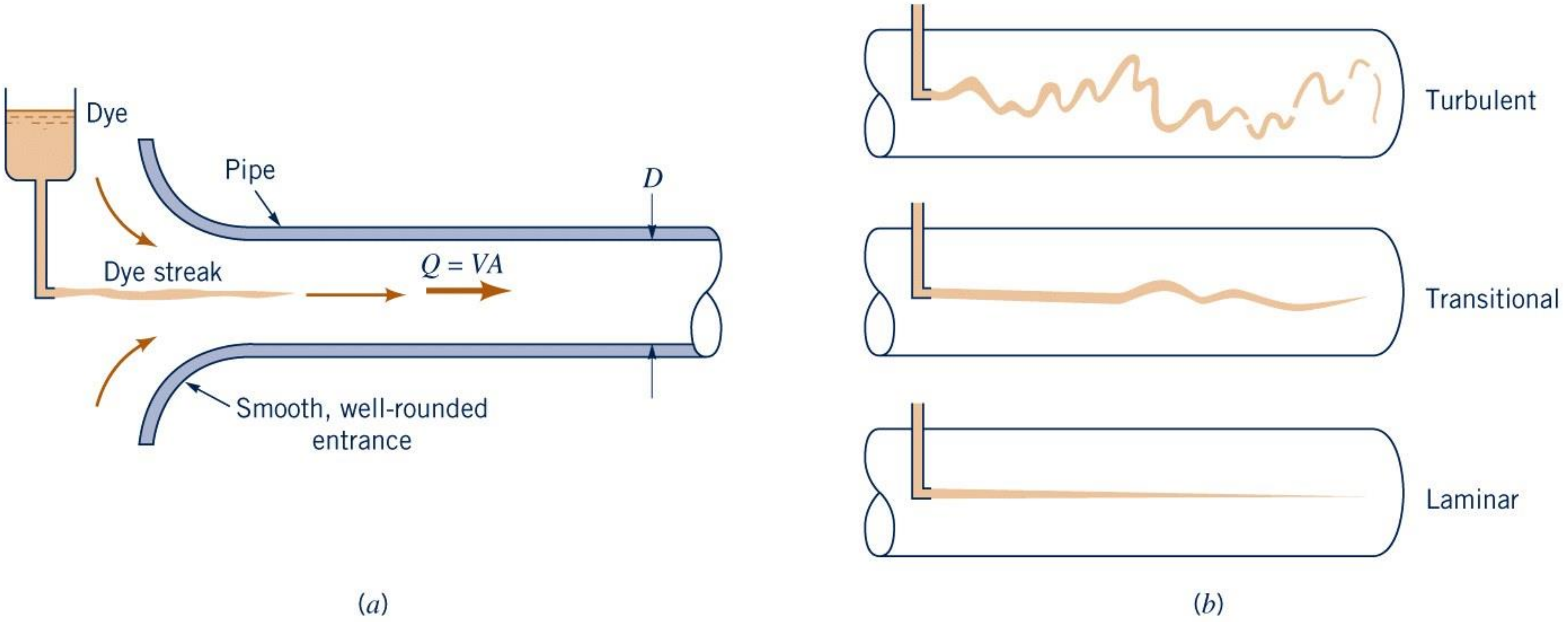


Figure 8.3
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## Typical dye streaks

# Time dependence of fluid velocity at a point

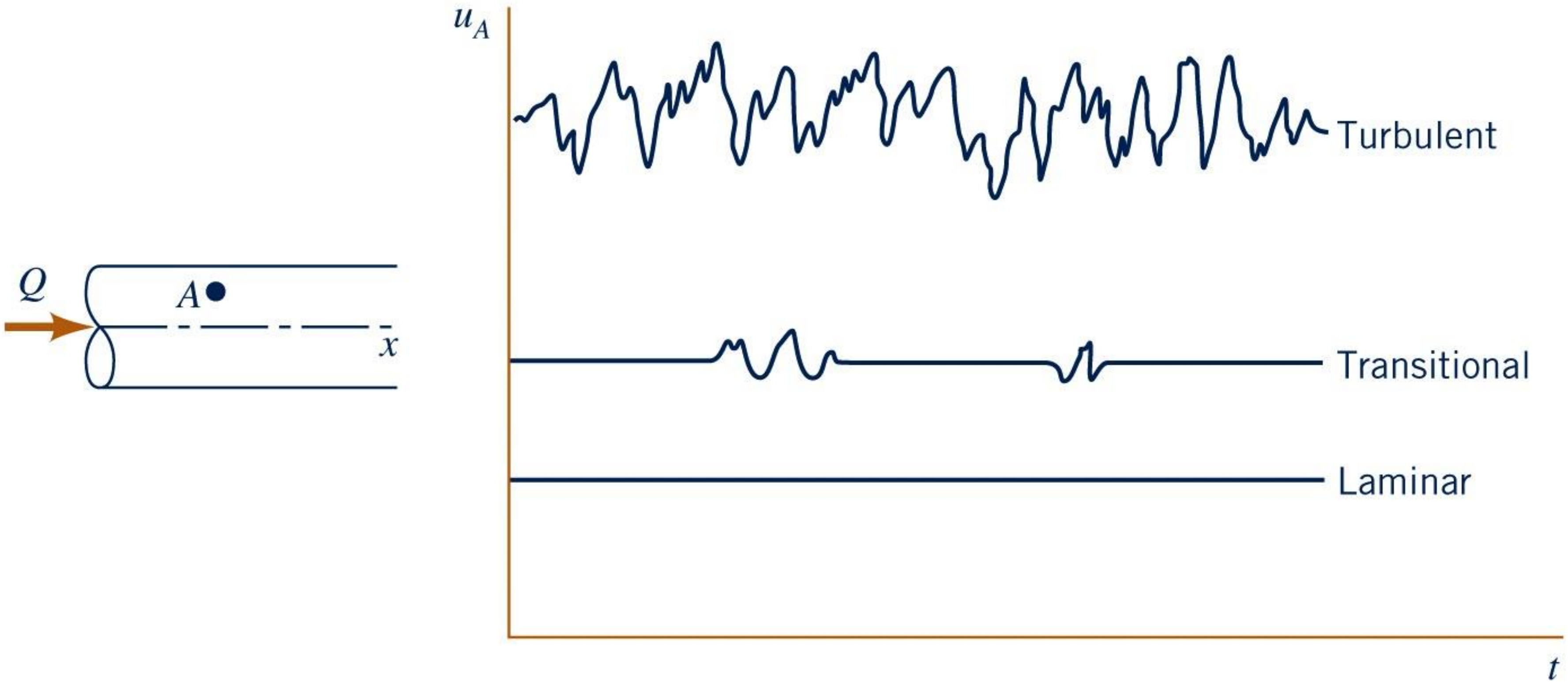


Figure 8.4
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