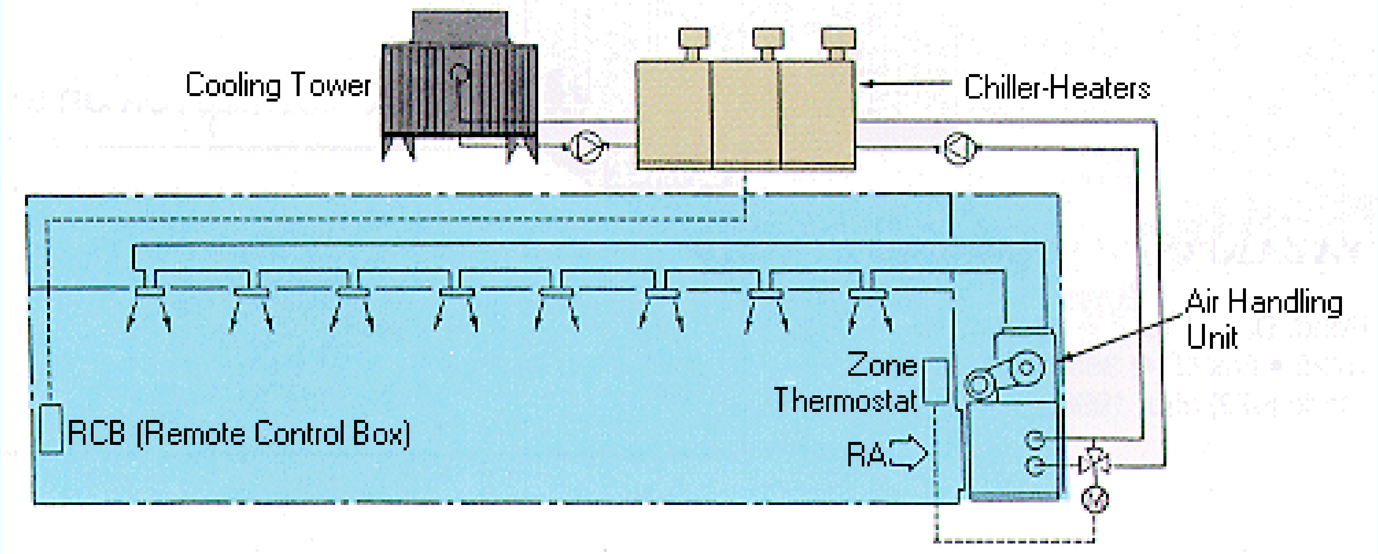
MEBS7014 Advanced HVAC applications

http://ibse.hk/MEBS7014/



Course Background

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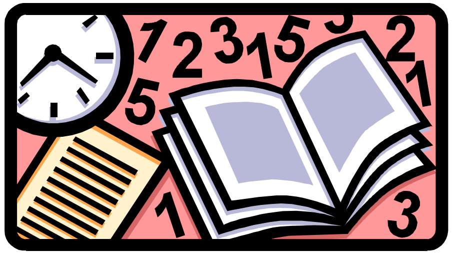
Dec 2022

About the Lecturer

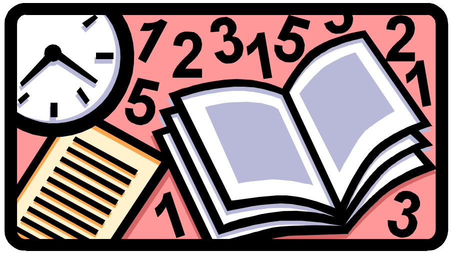
- ***Ir Dr. Sam C. M. Hui*** *許俊民 博士 工程師* http://ibse.hk/cmhui
  - Adjunct Assistant Professor 客席助理教授, HKU Dept of Mech Engg
  - PhD, BEng(Hons), CEng, CEM, BEMP, HBDP, MASHRAE, MCIBSE, MHKIE, MIESNA, LifeMAEE, AssocAIA
    - CEng = Chartered Engineer
    - CEM = Certified Energy Manager
    - BEMP = Building Energy Modeling Professional
    - HBDP = High-performance Building Design Professional
    - LifeMAEE = Life Member, Association of Energy Engineers
    - AssocAIA = Associate Member, American Institute of Architects
  - ASHRAE Distinguished Lecturer (2009-2011)
  - President, ASHRAE Hong Kong Chapter (2006-2007)

Course Background



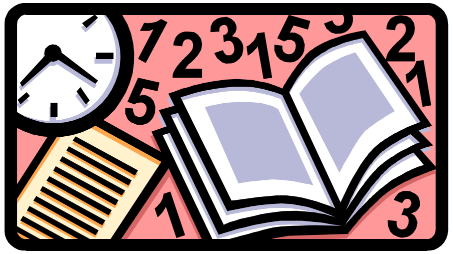
- Educational Objectives:
  - To introduce students to the important systems and applications of advanced HVAC for more detailed study.
  - To enable students to design appropriate heating, ventilating, air-conditioning and refrigerating (HVAC&R) systems and evaluate their characteristics and performance.

Course Background

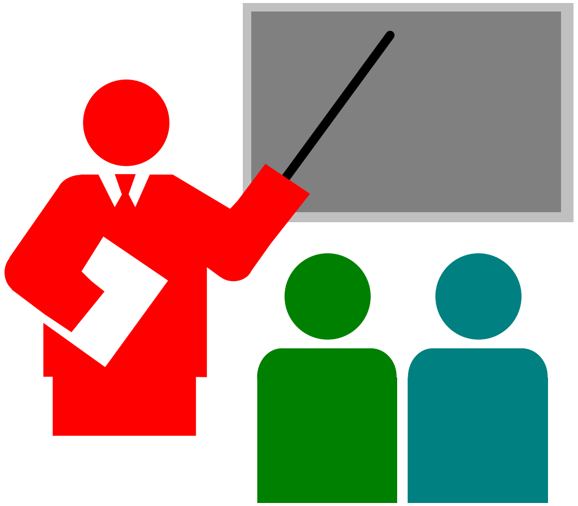


- Learning Outcomes:
  - To describe the basic principles and characteristics of HVAC systems and components.
  - To develop skills for design of HVAC&R systems and evaluation of their characteristics and performance.
- Assessment:
  - 60% Examination (2 hours), 40% Continuous Assessment (2 assignments)

Course Background



- Two related courses:
  - MEBS7012 Air conditioning and refrigeration
    - Basic principles of HVAC&R
    - Practical design skills
  - MEBS7014 Advanced HVAC applications
    - System characteristics and operation
    - Analysis and design strategies



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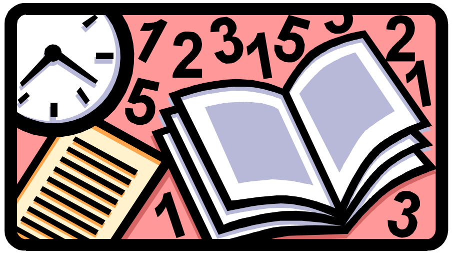
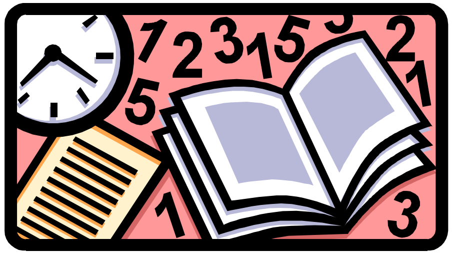
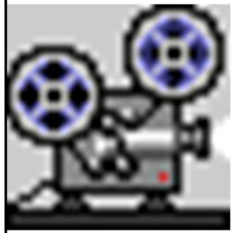


- Study topics of MEBS7014:
  - Fluid Network Analysis I & II
  - Fans and Pumps I & II
  - Space Air Diffusion I & II
  - Heat Recovery Systems I & II
  - Thermal Storage Systems I & II
  - Noise & Vibration Control I & II

Course Background

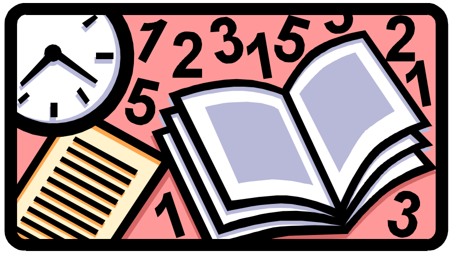


- Study methods
  - Lectures (core knowledge & discussions)
  - Further Readings (essential information for study)
  - Videos (illustration & demonstration)
  - References (useful supporting information)
  - Web Links (related links & resources)



- Assignments
  - Practical skills & applications

Course Background



- Recommended references:
  - ASHRAE, 2021. *ASHRAE Fundamentals Handbook 2017*, SI edition, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA. [ASHRAE catalog via Techstreet]
  - ASHRAE, 2020. *ASHRAE HVAC Systems and Equipment Handbook 2020*, SI edition, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA. [ASHRAE catalog via Techstreet]
  - Wang, S. K., 2001. *Handbook of Air Conditioning and Refrigeration*, 2nd ed., McGraw-Hill, New York. [697.93 W24 h]

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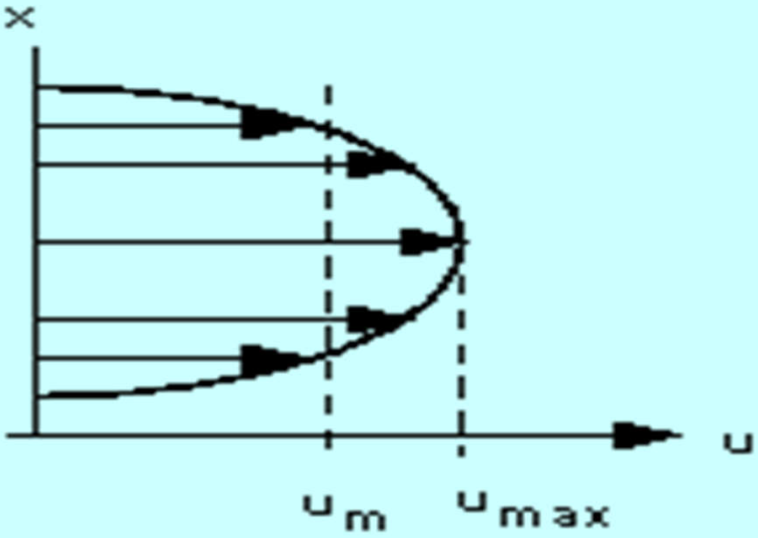

Fluid Network Analysis I

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Dec 2022

Contents

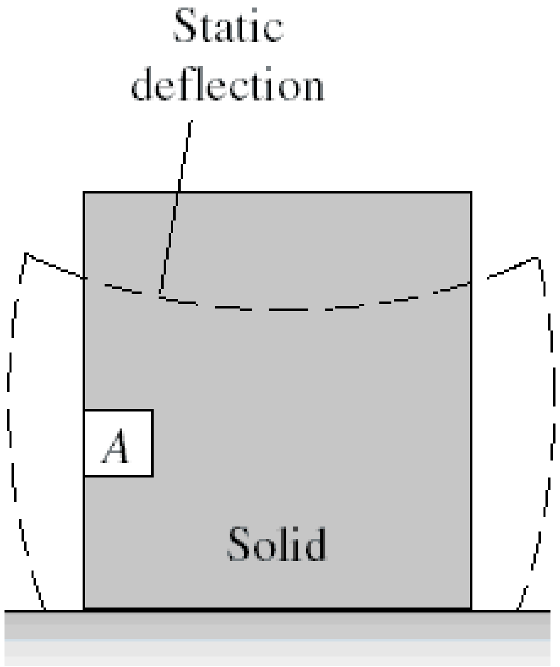
- Fluid Properties
- Fluid Dynamics
- Basic Flow Processes
- Flow Analysis

Fluid Properties

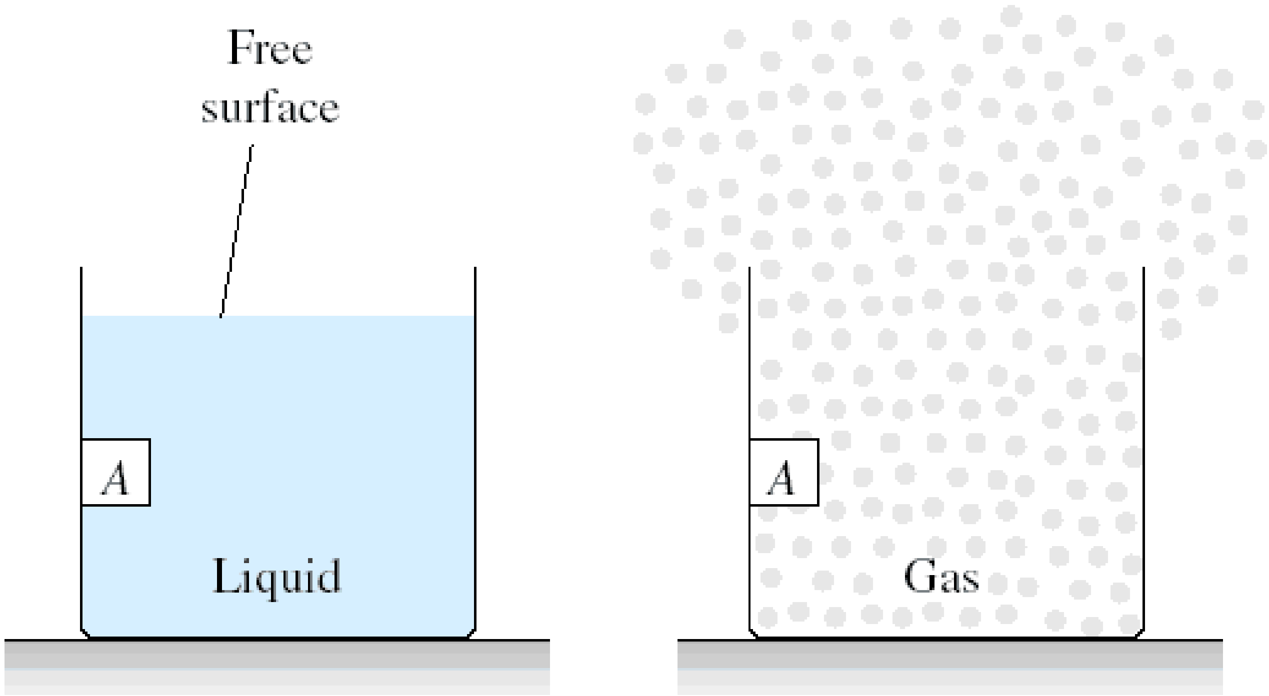
- HVAC (heating, ventilation & air-conditioning) processes
  - Often involve FLUID flows (e.g. air and water)
  - Understanding of fluid mechanics is important
- Fluid Mechanics – study of fluids at rest, in motion, and the effects of fluids on boundaries
  - Fluid statics
  - Momentum and energy analyses
  - Viscous effects and pressure forces

Fluids on boundaries

Solid



Liquid and Gas (fluids)



Fluid cannot resist shear.
Containing walls are needed.

Fluid Properties

- Under shear stress
  - A solid deforms only a finite amount
  - A fluid moves and deforms continuously
- Liquids and gases
  - Molecular actions
  - Degree of compressibility
- Two important properties
  - Pressure (static): $p_1 - p_2 = -\rho g\,(h_1 - h_2)$
  - Velocity (kinematic)

Fluid Properties

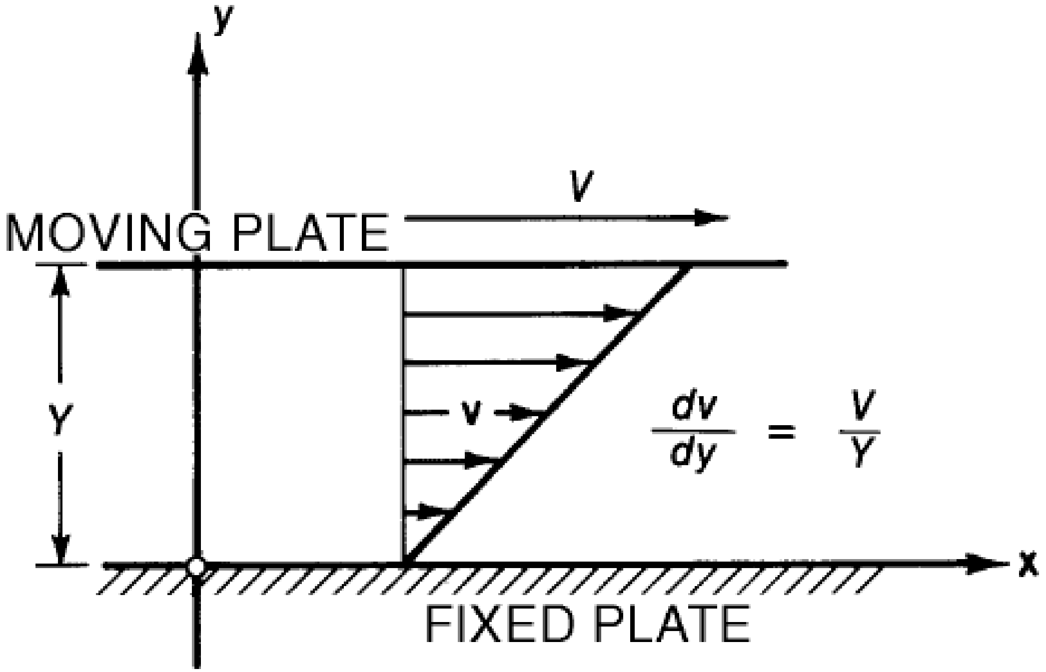
- Fluid motion
  - Ideal-fluid model: no resistance to shearing
    - Flow analysis is well developed
  - Real model: effects of viscous action
- Fluids in HVAC applications
  - Most of them are “Newtonian”*
    - Deformation is directly proportional to the shearing stress (Newtonian Law of Viscosity)
  - Viscosity does influence turbulence

* See also http://en.wikipedia.org/wiki/Newtonian_fluid

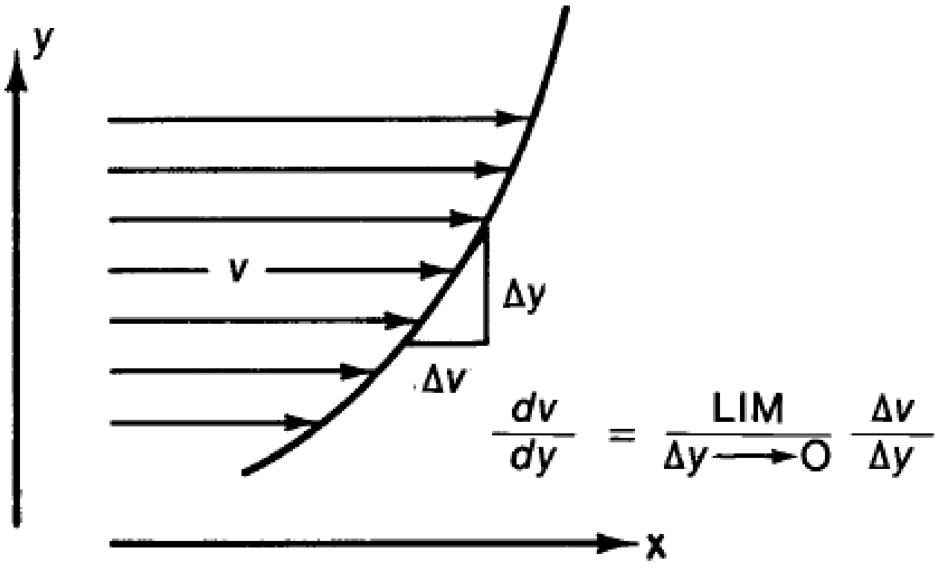
Fluid Properties

- Common fluid properties
  - Density (ρ): mass per unit volume
    - Density of water = 998 kg/m^3
    - Density of air = 1.20 kg/m^3
  - Viscosity: resistance of fluid layers to shear
    - $F / A = \mu (V / Y)$
      - F = tangential force
      - A = area of the plate
      - V = velocity
      - Y = separation distance
      - μ = absolute viscosity or dynamic viscosity

Velocity profiles and gradients in shear flows



A. SIMPLE FLOW OF LINEAR PROFILE



B. NONLINEAR PROFILE

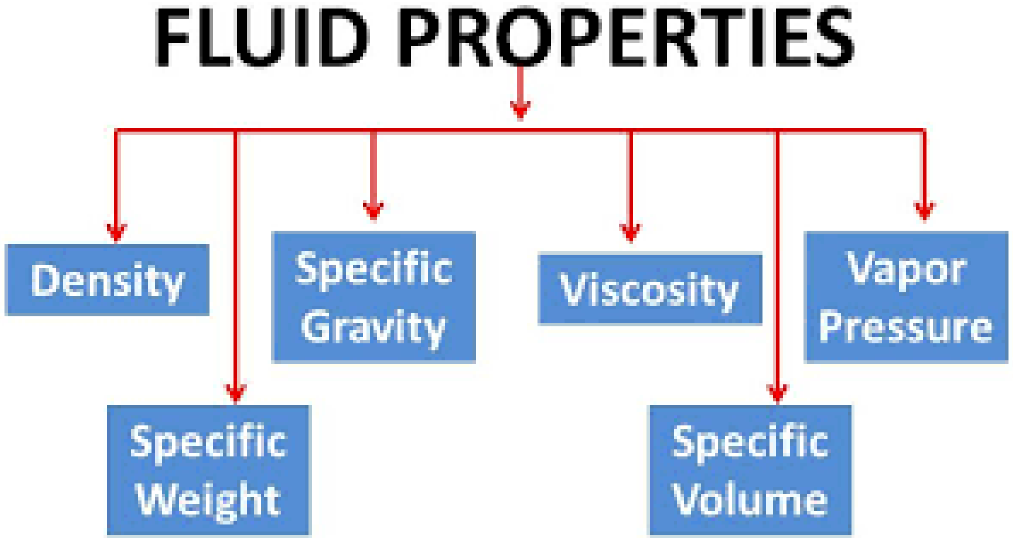
(Source: *ASHRAE Fundamentals Handbook 2001*)

Fluid Properties

- Viscosity (黏度) in complex flows
  - $F/A = \tau$ = shearing stress
  - V/Y = lateral velocity gradient
  - Therefore, $\tau = \mu\,(dV\,/\,dY)$
- Absolute viscosity (μ)
  - Depends on temperature
  - μ of water = 1.0 mN.s/m^2
  - μ of air = 18 μN.s/m^2

Fluid Properties

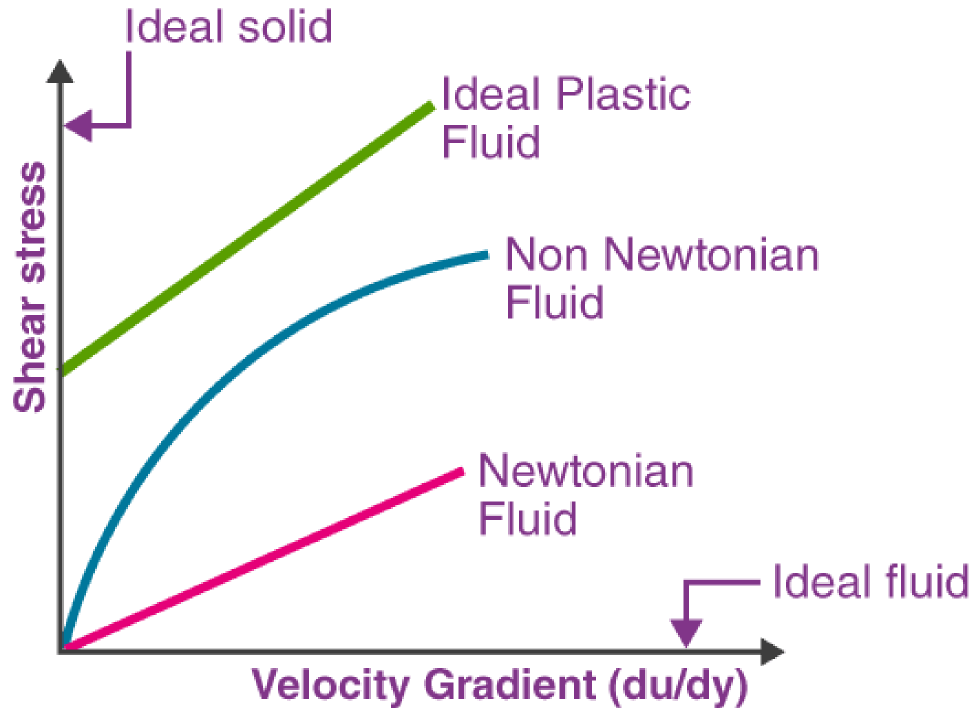
- Kinematic viscosity (ν): ratio of absolute viscosity to density
  - $\nu = \mu / \rho$
  - ν of water = 1.00 mm^2/s
  - ν of air = 16 mm^2/s



- Thermophysical Properties of Fluid Systems https://webbook.nist.gov/chemistry/fluid/

Density and viscosity of different types of fluids

Types of fluid	**Density**	**Viscosity**
Ideal fluid	Constant	Zero
Real fluid	Variable	Non-zero
Newtonian fluid	Constant/Variable	$\tau = \mu \, (dV / dY)$
Non-Newtonian fluid	Constant/Variable	$\tau \neq \mu \, (dV / dY)$
Incompressible fluid	Constant	Non-zero/zero
Compressible fluid	Variable	Non-zero/zero



(Source: https://byjus.com/physics/fluid-flow/)

Fluid Properties

- Useful reference:
  - ASHRAE, 2021. *ASHRAE Fundamentals Handbook 2021*, SI edition, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA. [ASHRAE catalog via Techstreet]
    - Chapter 1 Psychrometrics (Moist Air & Water)
    - Chapter 3 Fluid Flow
    - Chapter 5 Two-phase Flow
    - Chapter 20 Space Air Diffusion
    - Chapter 21 Duct Design
    - Chapter 22 Pipe Design

Fluid Dynamics

- Physical laws for homogenous, constant-property, incompressible fluids
- Continuity: conservation of matter
  - $\int$(density x velocity) dA = constant
  - For constant cross-sectional area,
    - Mass flow rate = $\rho V A$ = constant
  - When flow is incompressible, ρ is constant, then
    - Volume flow rate = $V A$ = constant

Fluid Dynamics

- Pressure variation across flow
  - Variation across streamlines involves fluid rotation (vorticity 渦度)
  - Lateral pressure variation across streamlines is given by:

$$\boxed{\frac{\partial}{\partial r}\left(\frac{p}{\rho}+gz\right)=\frac{v^2}{r}}$$

r = radius of curvature of streamline

z = elevation

  - This equation explains
    - Pressure difference between the inside & outside walls of a bend and near other regions of section change
    - That pressure variation is hydrostatic ($p + \rho\, g\, z$) = constant

Fluid Dynamics

- Bernoulli equation *
  - Basic tool for fluid flow analysis
  - Apply first law of thermodynamics
    - $\Delta E =$ Work done (W) + Heat absorbed (Q)
  - Fluid energy is composed of kinetic, potential and internal (u) energies. Per unit mass of fluid, the energy change is:

$$\underbrace{\Delta\left(\frac{v^2}{2} + gz + u\right)}_{\text{Fluid energy}} = \underbrace{E_M}_{\text{External work}} - \underbrace{\Delta\left(\frac{p}{\rho}\right)}_{\text{Pressure/flow work}} + Q$$

* See also http://en.wikipedia.org/wiki/Bernoulli's_principle

Fluid Dynamics

- Bernoulli equation (cont'd)
  - Rearrange the equation,

$$\Delta\left(\frac{v^2}{2}+gz+\frac{p}{\rho}\right)+\Delta u = E_M - Q$$

  - Bernoulli constant = $\pi = \dfrac{p}{\rho}+\dfrac{v^2}{2}+gz$ ← Energy per volume flow
  - Alternative forms:

Energy per mass flow → $p+\dfrac{\rho v^2}{2}+\rho gz = \rho\pi$

For liquid flow (or head) → $\dfrac{p}{\rho g}+\dfrac{v^2}{2g}+z = \dfrac{\pi}{g}$

Fluid Dynamics

- Many pipe/duct systems can be considered as "one-dimensional flow"
  - Use Bernoulli equation to analyse velocity and pressure
  - For steady flow, irrotational, incompressible flow,

$$\underbrace{\frac{p}{\rho g}}_{\text{Pressure head}} + \underbrace{\frac{v^2}{2g}}_{\text{Velocity head (kinetic)}} + \underbrace{z}_{\text{Potential head (elevation)}} = \underbrace{\text{constant}}_{\text{Total head}}$$

Fluid Dynamics

- If the section-average velocity (V) is used, the kinetic energy term of the Bernoulli constant ($v^2/2$) is expressed as ($\alpha V^2/2$),
  - where α = kinetic energy factor (ratio of true kinetic energy of the velocity profile to that of the mean flow velocity)
  - For laminar flow in a wide rectangular channel, $\alpha = 1.54$; for a pipe, $\alpha = 2.0$

Fluid Dynamics

- Assume $Q = 0$, Bernoulli equation can be used to determine the change in energy between two stations

External work

Change of internal energy, Δu

$$\left(\frac{p}{\rho}+\alpha\frac{V^2}{2}+gz\right)_1+E_M=\left(\frac{p}{\rho}+\alpha\frac{V^2}{2}+gz\right)_2+E_L$$

- Or, dividing by g,

$$\left(\frac{p}{\rho g}+\alpha\frac{V^2}{2g}+z\right)_1+H_M=\left(\frac{p}{\rho g}+\alpha\frac{V^2}{2g}+z\right)_2+H_L$$

Fluid Dynamics

- Laminar flow (層流)
  - For steady, fully developed laminar flow in a parallel-walled conduit, the shear stress τ varies linearly with distance *y* from the centerline
  - For a wide rectangular channel,

$$\tau = \left(\frac{y}{b}\right)\tau_w = \mu\frac{dv}{dy}$$

    - τ_w = wall shear stress = $b\,(dp/ds)$
    - $2b$ = wall spacing
    - s = flow direction
  - Because velocity = 0 at the wall ($y = b$), the integrated result is:

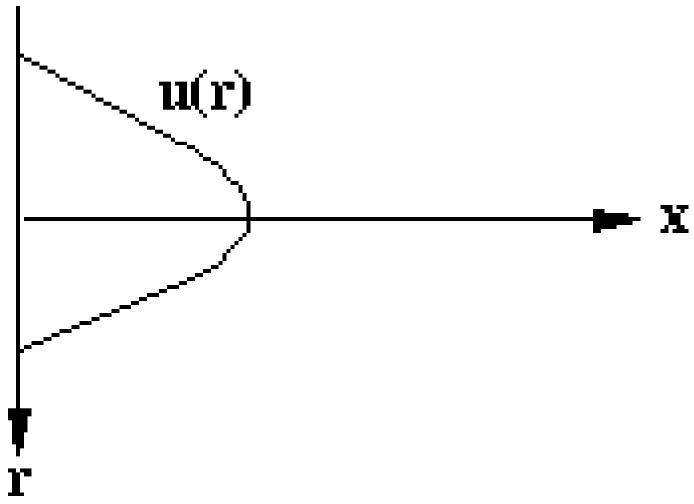
$$v = \left(\frac{b^2 - y^2}{2\mu}\right)\frac{dp}{ds}$$

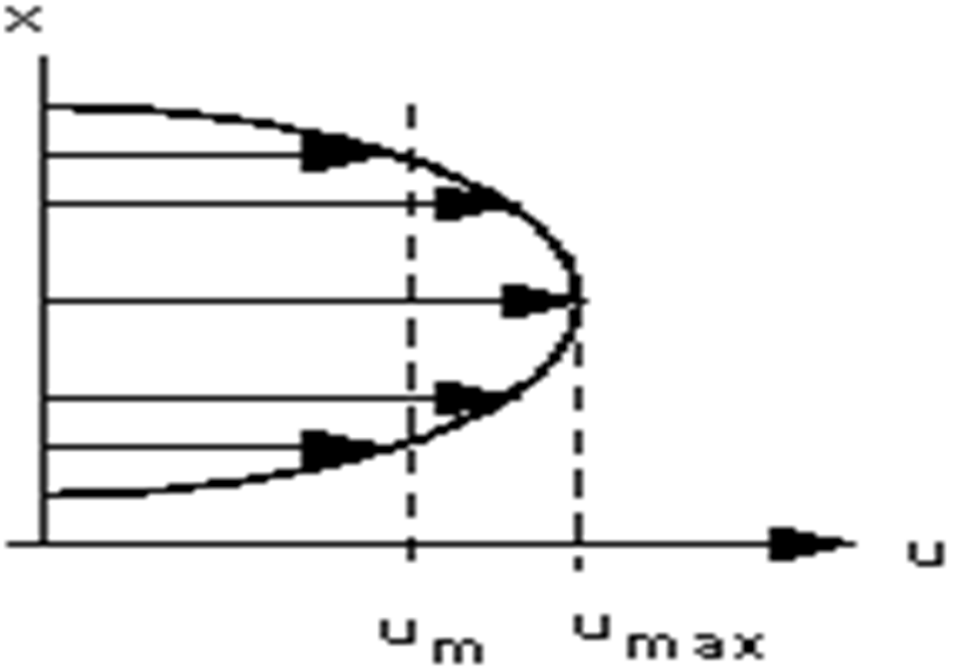
Poiseuille-flow parabolic velocity profile

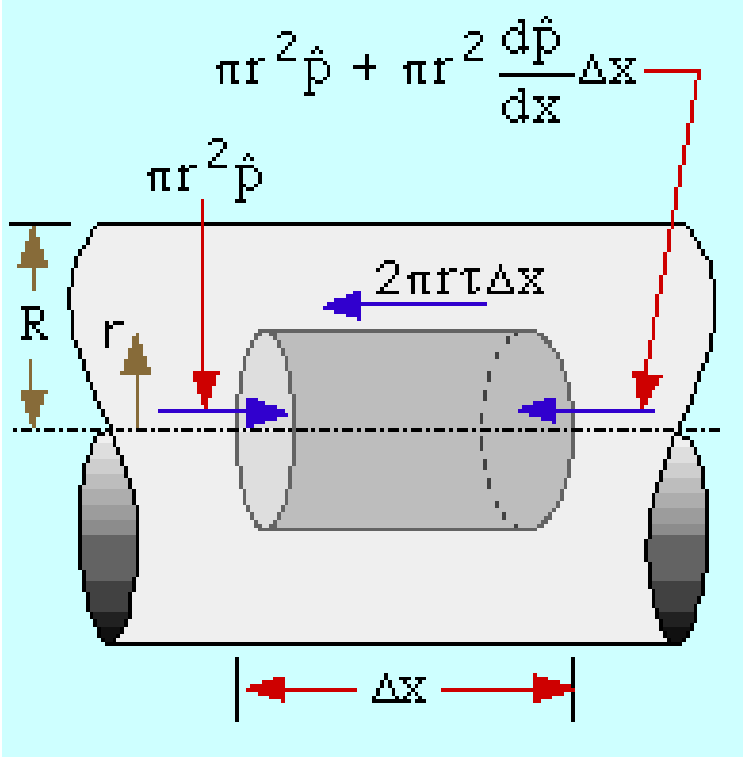
Fluid Dynamics

- Laminar flow (cont'd)
  - Average velocity $V = 2/3$ of max. velocity (at $y = 0$)
  - Longitudinal pressure drop in terms of conduit flow velocity is: $$\frac{dp}{ds} = -\left(\frac{3\mu V}{b^2}\right)$$
  - For axisymmetric conduit (pipe) of radius R, the parabolic velocity profile can be derived. The average velocity $V =$ ½ of max. velocity, and pressure drop is: $$\frac{dp}{ds} = -\left(\frac{8\mu V}{R^2}\right)$$

Velocity profiles in laminar flow

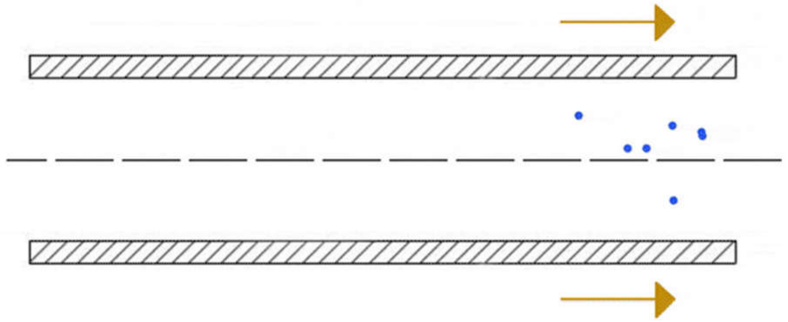






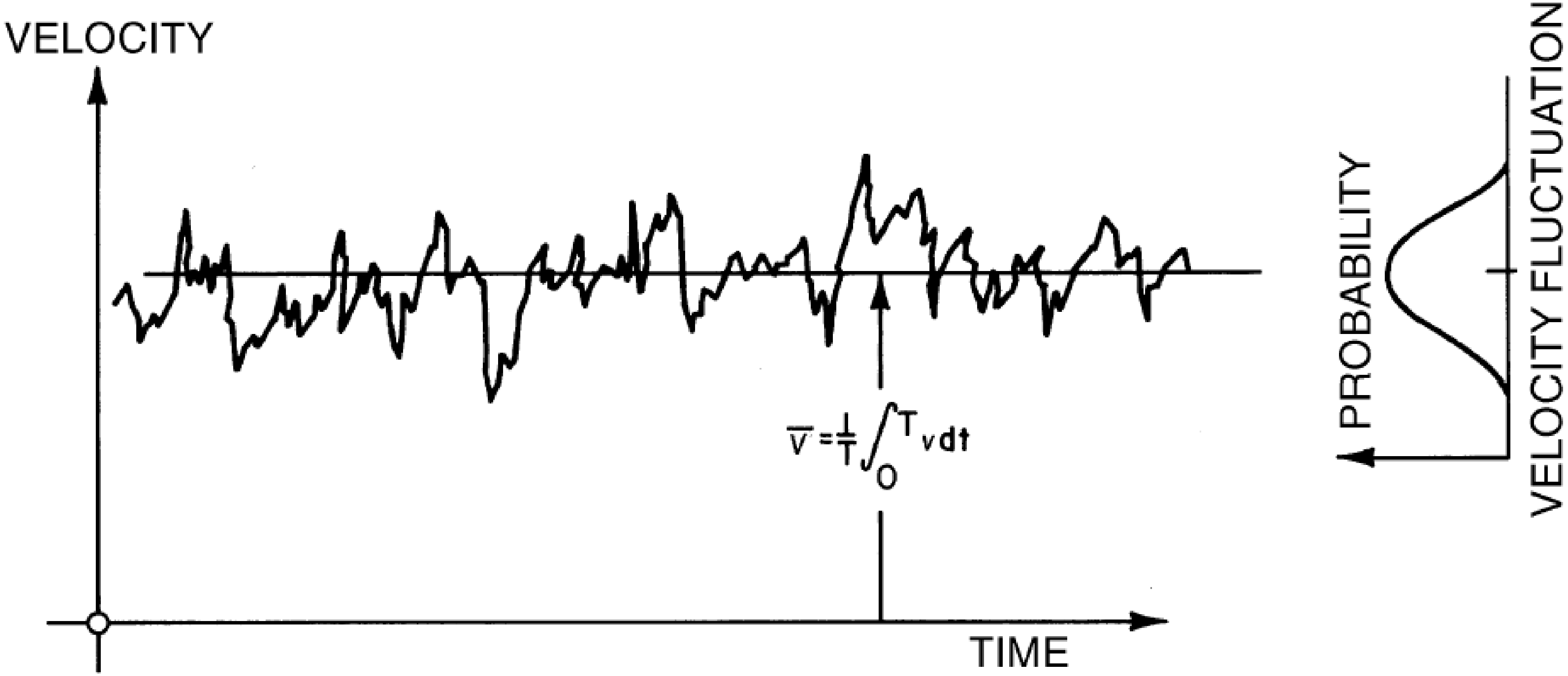
Fluid Dynamics

- Turbulent flow (湍流)
  - Random fluctuations of flow (velocity & pressure)
    - Without any order or periodicity
  - Can be quantified by statistical factors
    - "Strength of turbulence" is characterized by the root-mean-square of the instantaneous velocity variation about the mean velocity
  - Effect of turbulence
    - Cause the fluid to diffuse momentum, heat and mass very rapidly across the flow



turbulent flow

Velocity fluctuation at point in turbulent flow



(Source: *ASHRAE Fundamentals Handbook 2001*)

Fluid Dynamics

- Reynolds number (Re): dimensionless, gives the relative ratio of inertial to viscous forces
  - $\mathrm{Re} = V L / \nu = \rho V L / \mu$
    - V = velocity of fluid
    - L = characteristics length (For pipes, L = diameter)
    - ν = kinematic viscosity
    - ρ = density of fluid
    - μ = absolute viscosity
  - Laminar flow if $\mathrm{Re} < 2000$; fully turbulence if $\mathrm{Re} > 10000$
  - Transition state if $2000 < \mathrm{Re} < 10000$

Fluid Dynamics

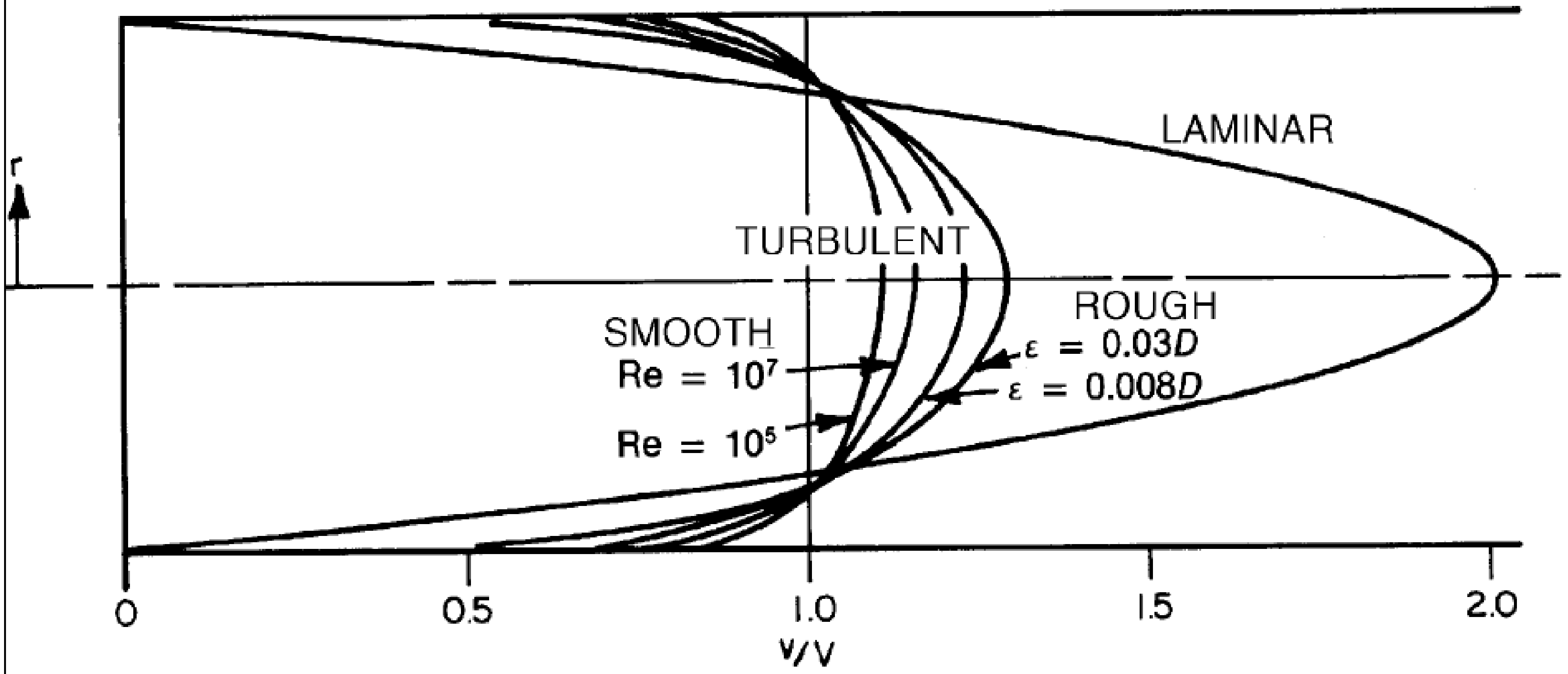
- Videos for illustration:

  - Understanding Bernoulli's Equation (13:43) https://youtu.be/DW4rItB20h4
  - Understanding Laminar and Turbulent Flow (14:58) https://youtu.be/9A-uUG0WR0w
  - Fluid flow visualization
    - Flow past cylinder: Karman vortex Street - experimental (0:10) http://youtu.be/CB2aWiesq0g
    - Experimental flow separation (0:37) http://youtu.be/Vjk9Ux2COx0

Basic Flow Processes

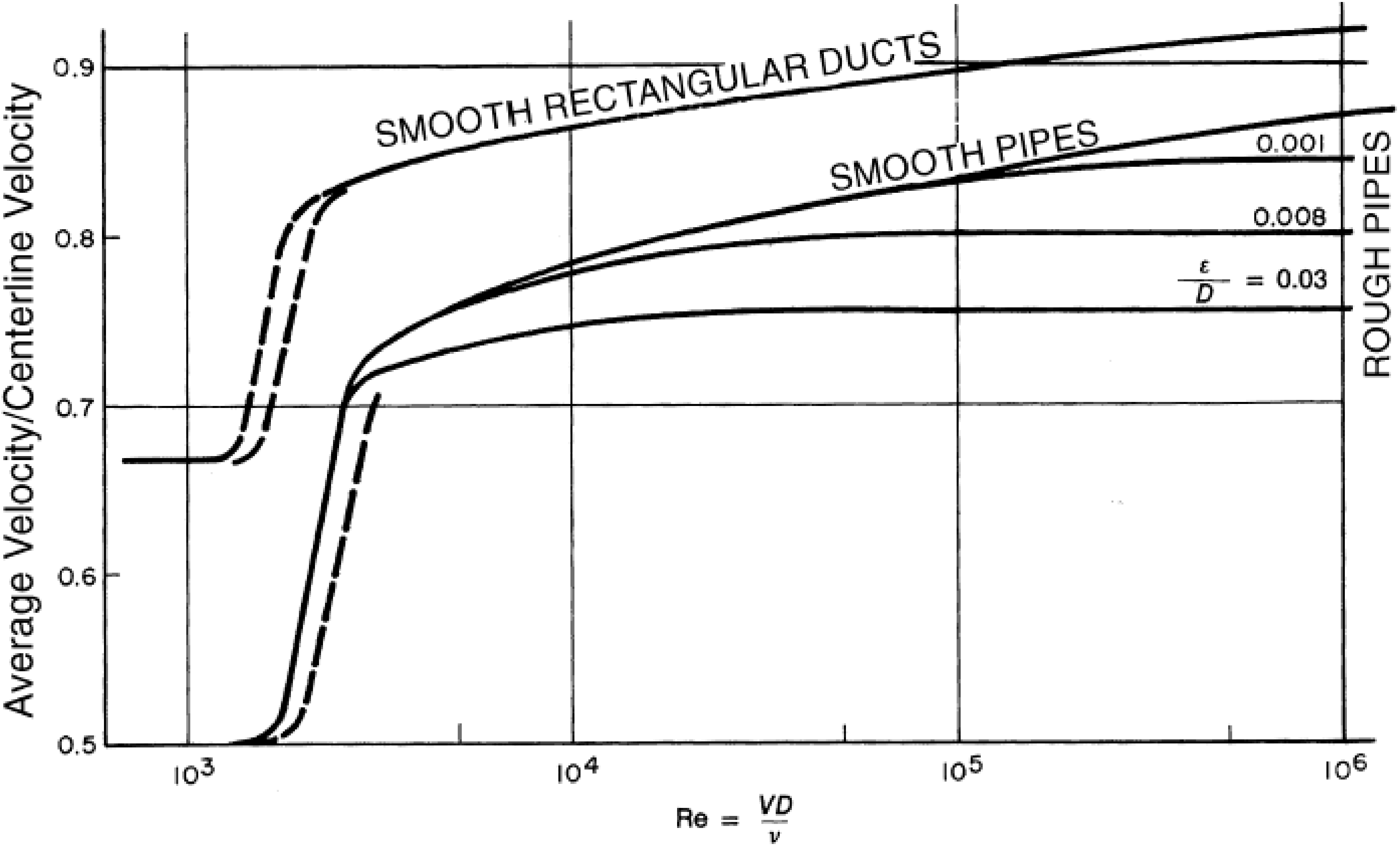
- Wall friction
  - At the boundary of real-fluid flow, the relative tangential velocity at fluid surface is zero
    - High shear stress near the wall boundary
    - Slowing down of adjacent fluid layers
  - Velocity profiles near a wall
    - Laminar and turbulent flow differ significantly
    - Pipe factor = ratio of average to max. (centreline) velocity

Velocity profiles of flow in pipes



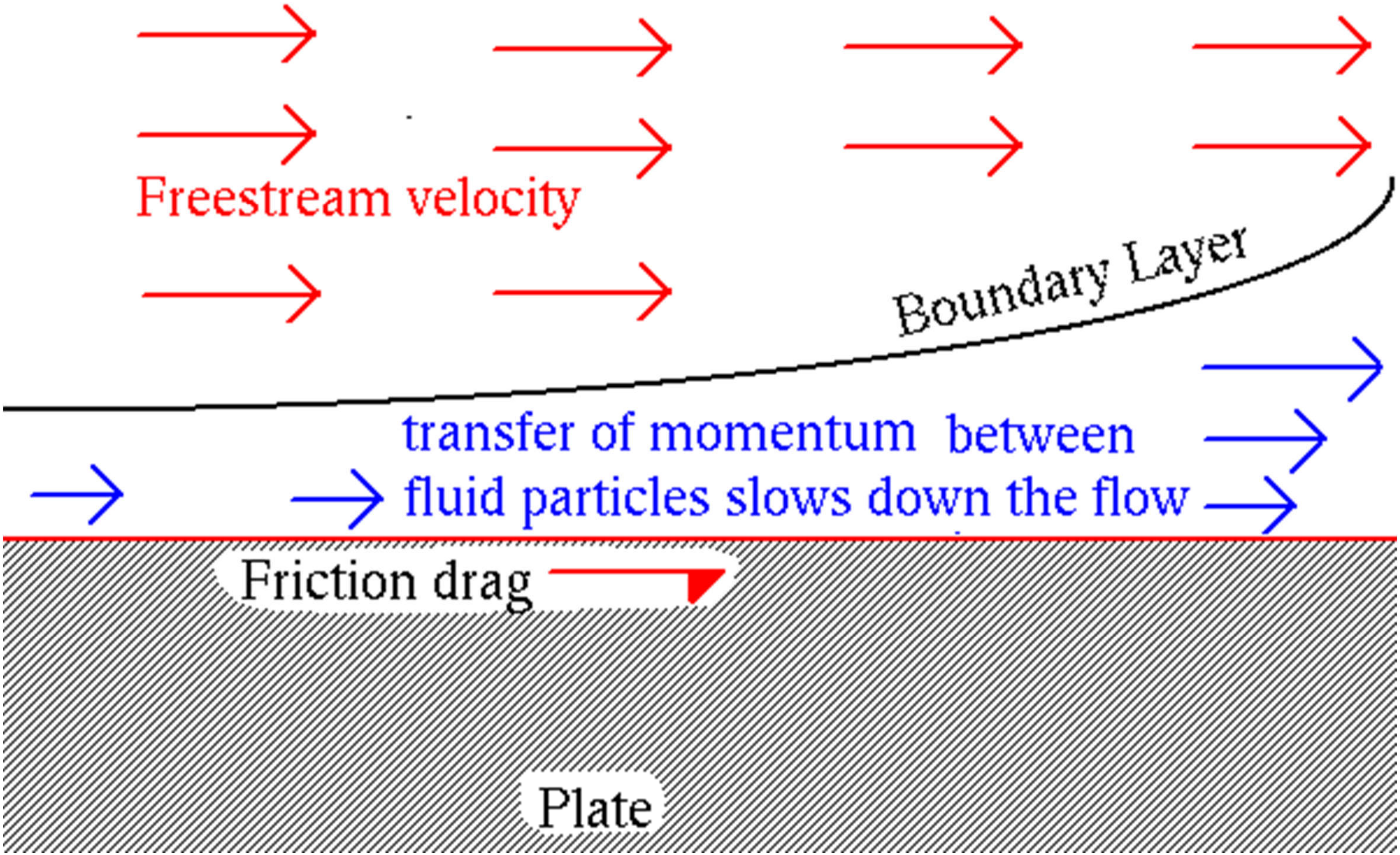
(Source: *ASHRAE Fundamentals Handbook 2001*)

Pipe factor for flow in conduits



(Source: *ASHRAE Fundamentals Handbook 2001*)

Boundary layer in fluid flow

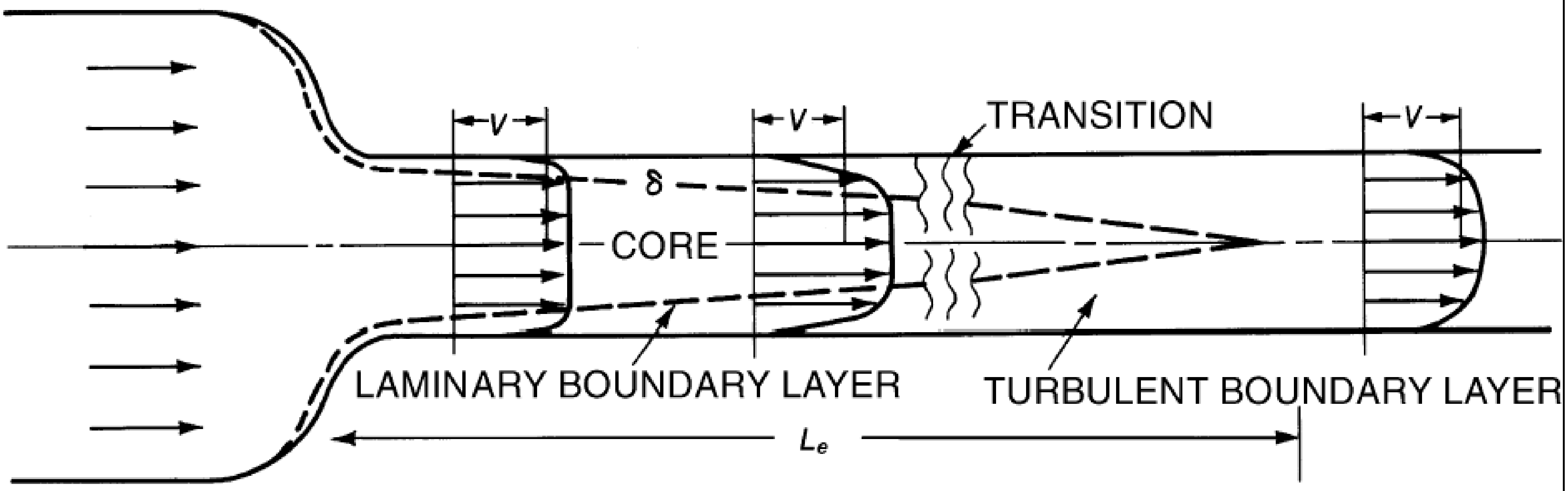


Source: Computer Aided Learning In Fluid Dynamics http://cvu.strath.ac.uk/courseware/calf/CALF/index/web_calf.html

Basic Flow Processes

- Boundary layer
  - Encompasses all viscous or turbulent actions
    - Causing velocity to increase rapidly from zero to that of outer flow edge
  - Generally laminar near the start of their formation, but may become turbulent downstream
  - For conduit flows, pipe diameter is small compared with distances in flow direction
    - Layers from walls will meet at the centreline

Flow in conduit entrance region



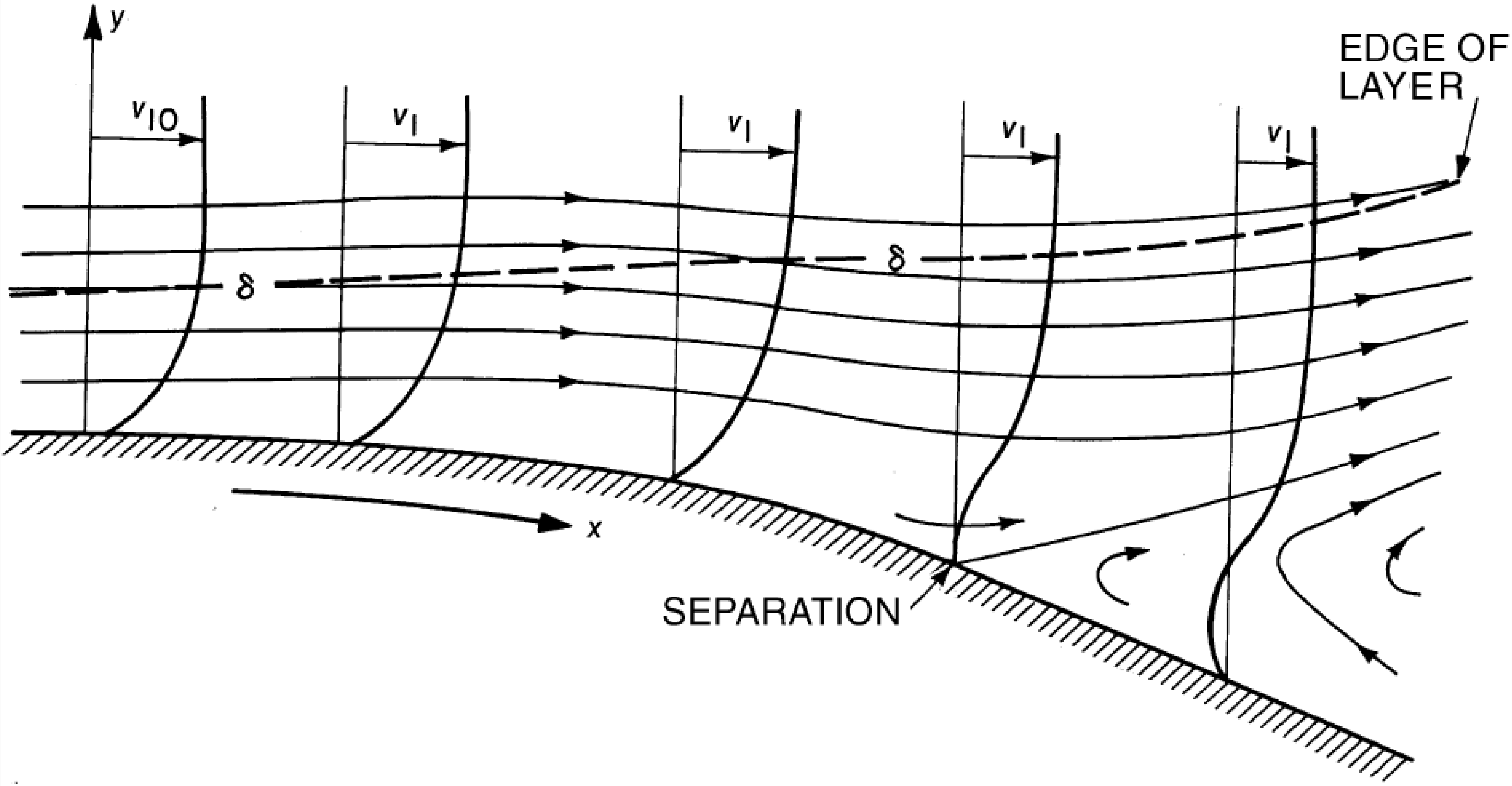
Distance in flow direction foreshortened.

(Source: *ASHRAE Fundamentals Handbook 2001*)

Basic Flow Processes

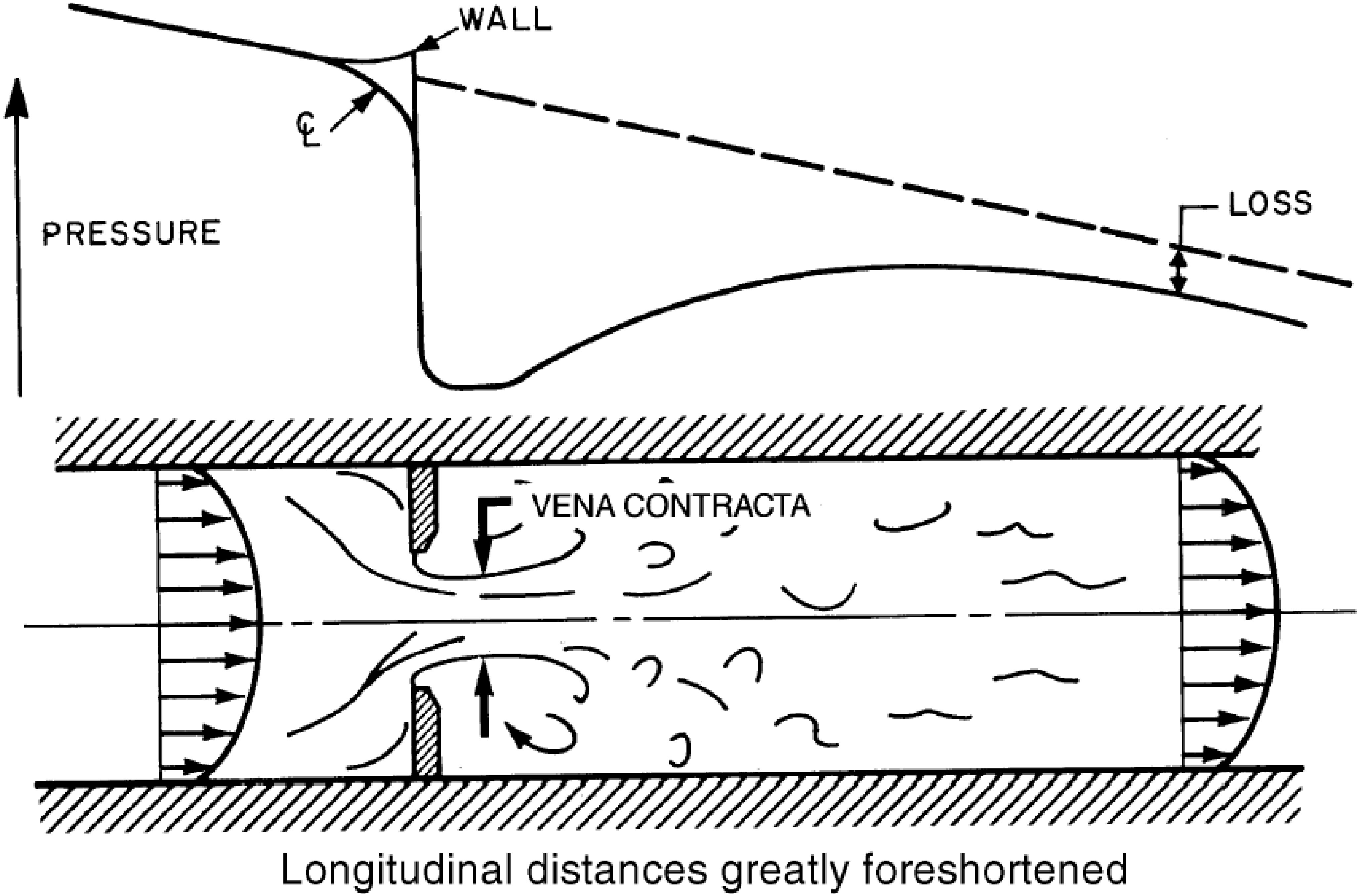
- In some boundary-layer flows, pressure gradient effects can be severe and may even lead to “separation” (fluid may backflow near the wall)
- Flow separation is due to frictional velocity reduction near the wall (difficult to predict)
    - Dynamic separation (dynamic growth of boundary)
    - Geometric separation (e.g. pass over a sharp corner or sharp entrance or sudden expansion)

Boundary layer flows to separation



(Source: *ASHRAE Fundamentals Handbook 2001*)

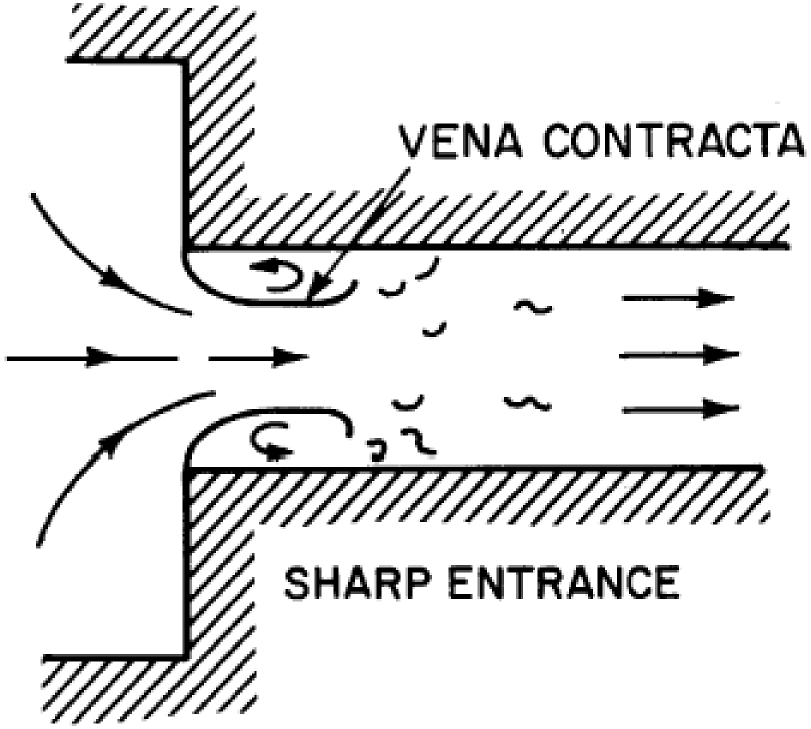
Geometric separation, flow development and loss in flow through orifice

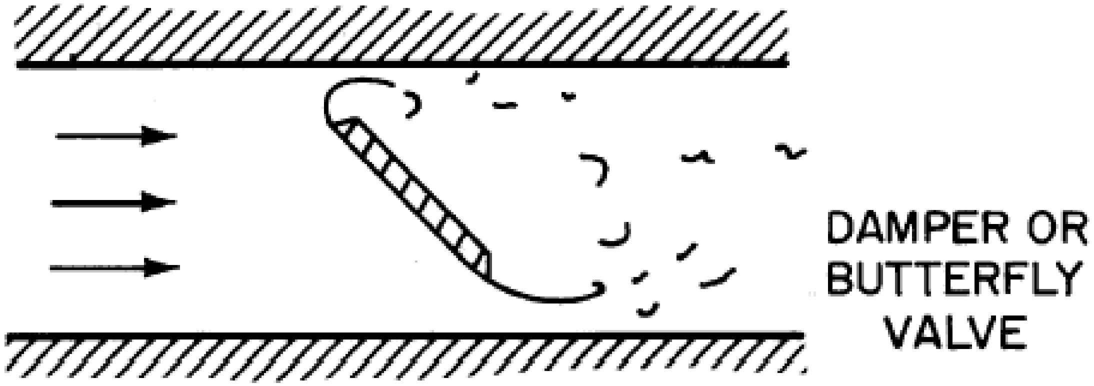


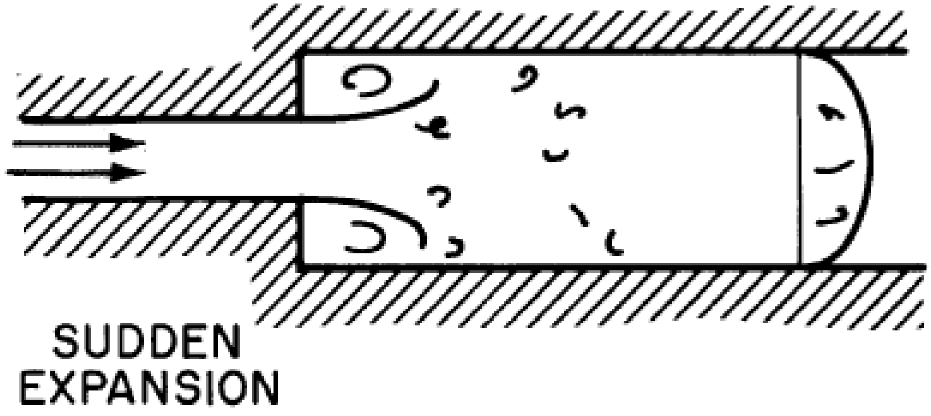
Longitudinal distances greatly foreshortened

(Source: *ASHRAE Fundamentals Handbook 2001*)

Examples of geometric separation in flows in conduits





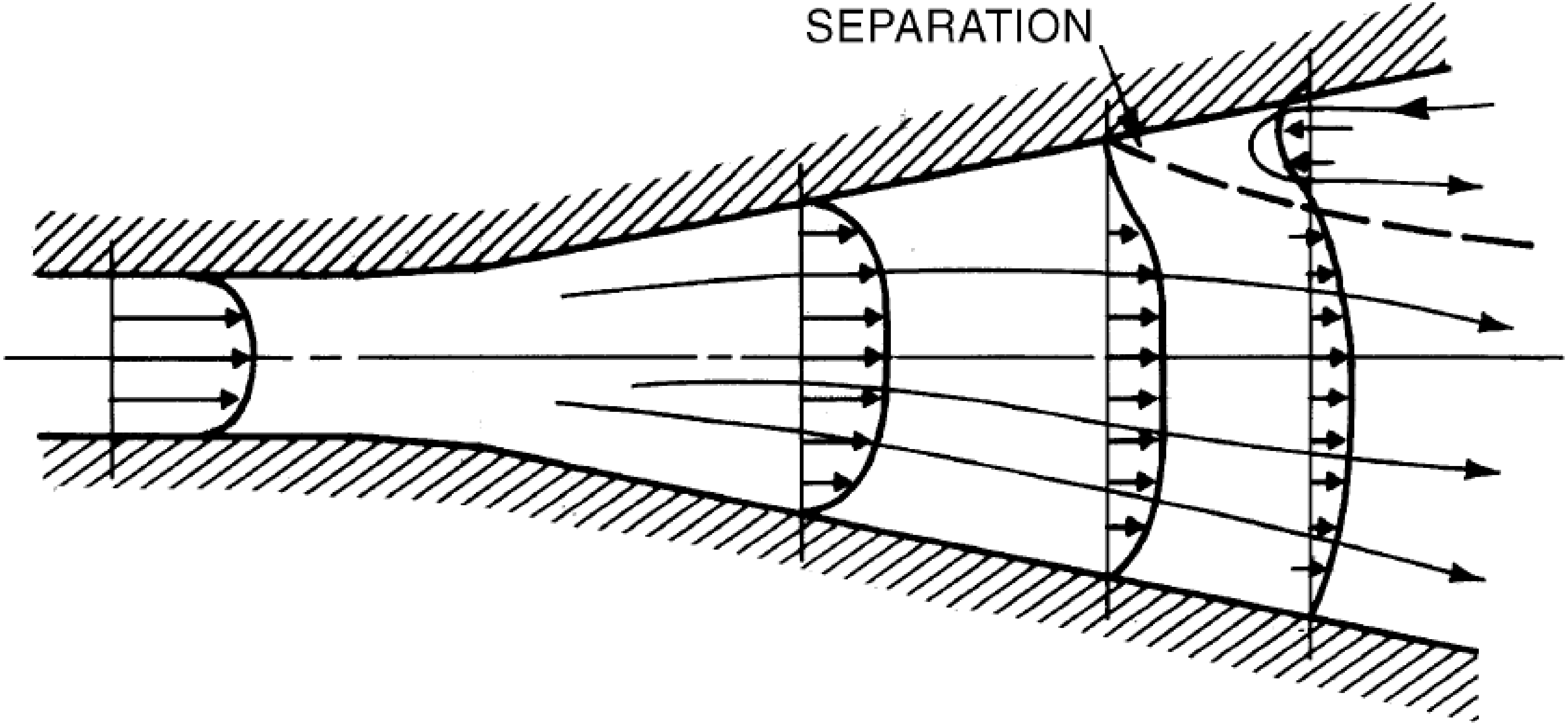


(Source: *ASHRAE Fundamentals Handbook 2001*)

Basic Flow Processes

- Flow separation in diffuser
  - To expand a flow efficiently, the device shall be designed with gradual contours, a diffuser, or a rounded entrance
  - To control separation
    - May use splitters to divide the diffuser into smaller divisions less likely to have separations
    - May bleed some low-velocity fluid near the wall

Separation in flows in diffuser



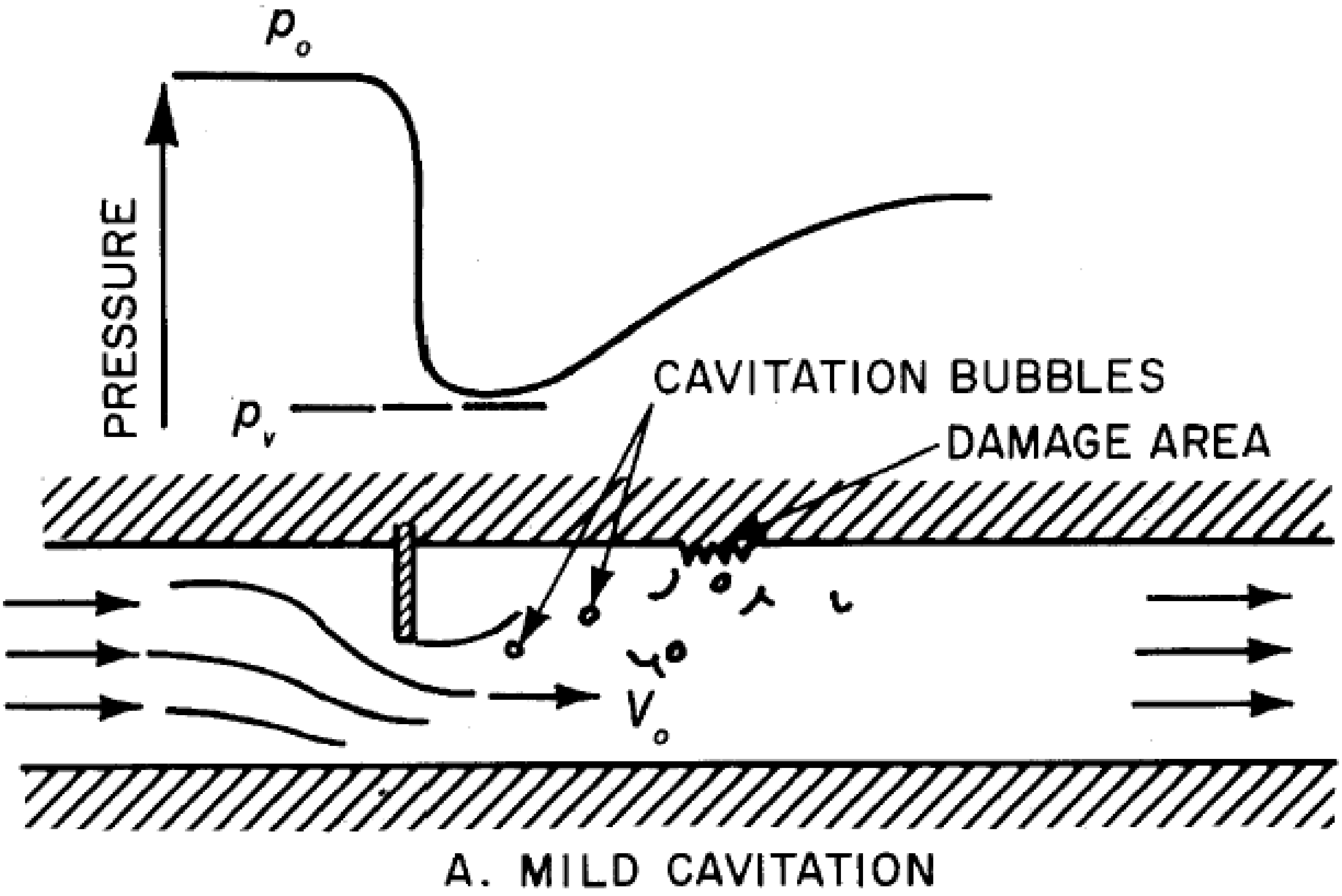
(Source: *ASHRAE Fundamentals Handbook 2001*)

Basic Flow Processes

- Cavitation* (空穴現象, 穴 蝕, 孔蝕)
  - Liquid flow with gas- or vapour-filled pockets can occur if the absolute pressure is reduced to vapour pressure or less
    - Collapse noise of many small bubbles
    - More bubbles appear & may join to form large cavities
    - May modify flow pattern & alter device performance
    - Frequent collapse of cavities on or near solid boundaries may result in damage through cavitational erosion or excessive vibration

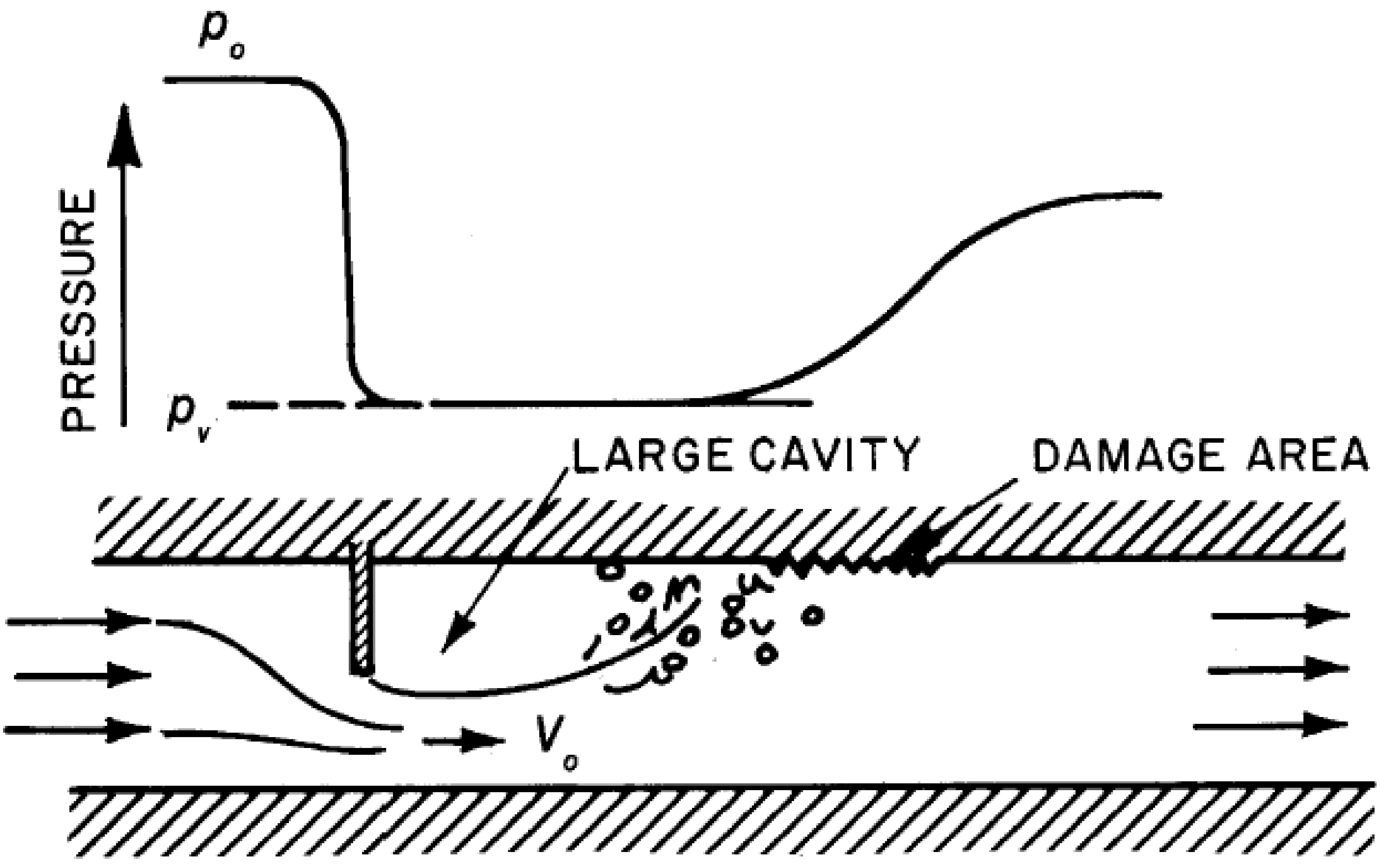
* See also http://en.wikipedia.org/wiki/Cavitation

Mild cavitation



(Source: *ASHRAE Fundamentals Handbook 2001*)

Extensive cavitation

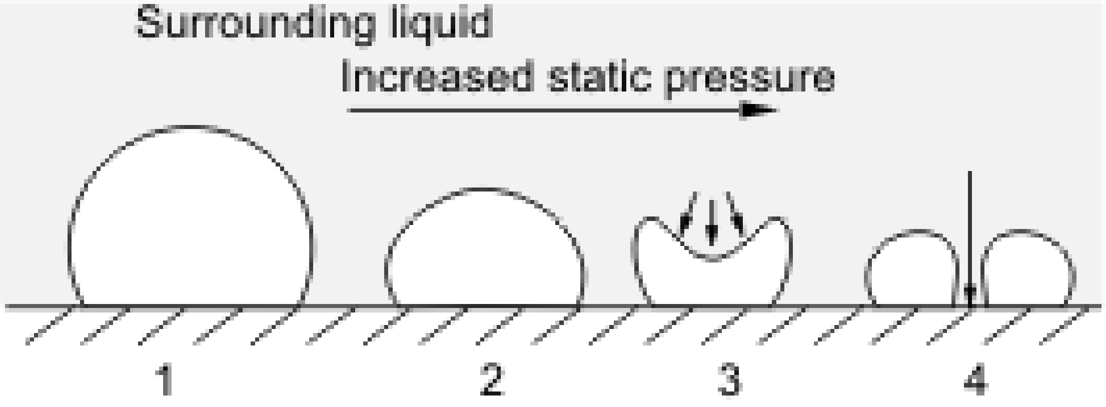


B. EXTENSIVE CAVITATION

(Source: *ASHRAE Fundamentals Handbook 2001*)

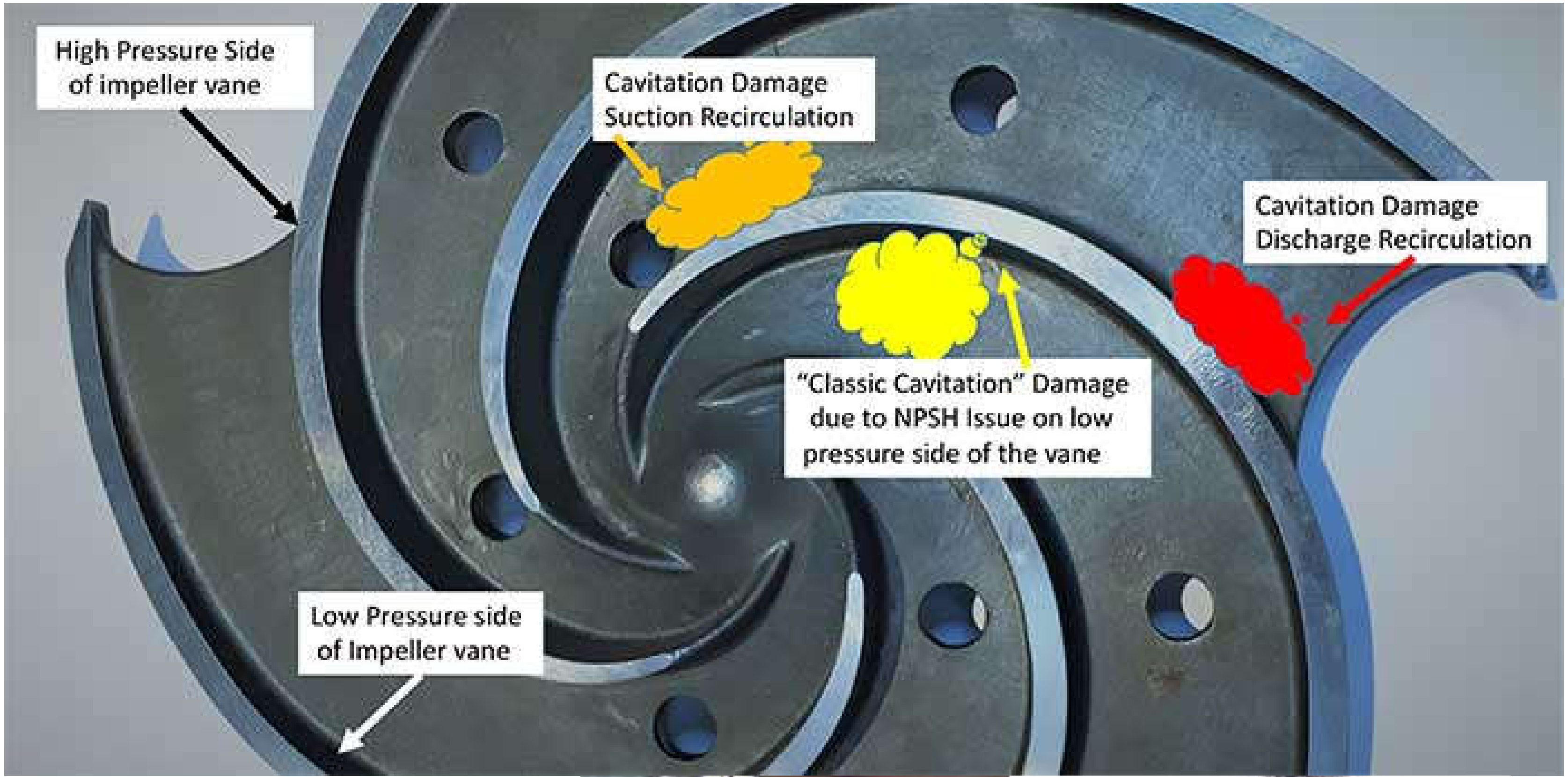
Basic Flow Processes

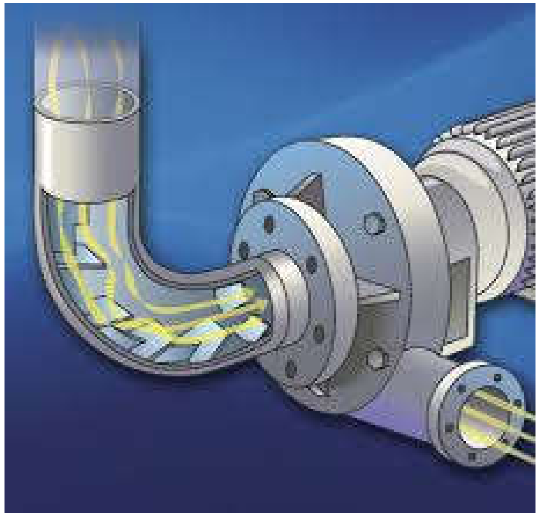
- Videos for illustration:
  - Cavitation - Easily explained! (10:11) https://youtu.be/U-uUYCFDTrc
  - What is Valve Cavitation? (Animation) (5:56) https://youtu.be/ZlrFMmGs_NI

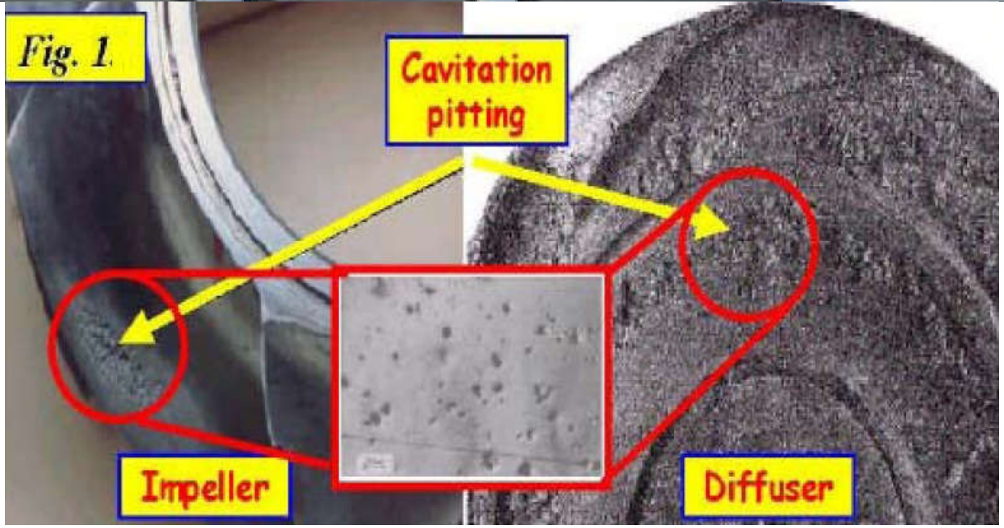


Cavitation bubble imploding close to a fixed surface generating a jet (4) of the surrounding liquid.

Cavitation pitting in pump impellers







(Image sources: https://www.pumpsandsystems.com/why-cavitation-occurs-ways-treat-it, http://steamofboiler.blogspot.com/2011/07/pump-cavitation.html)

Basic Flow Processes

- Methods to avoid cavitation
  - 1. Operate the device at high enough pressure
  - 2. Change the flow
  - 3. Device is built to withstand the cavitation effects (e.g. by surface coating)
  - 4. Design surface contours to delay the advent of cavitation
- See also: Why Cavitation Occurs & Ways to Treat it https://www.pumpsandsystems.com/why-cavitation-occurs-ways-treat-it

Flow Analysis

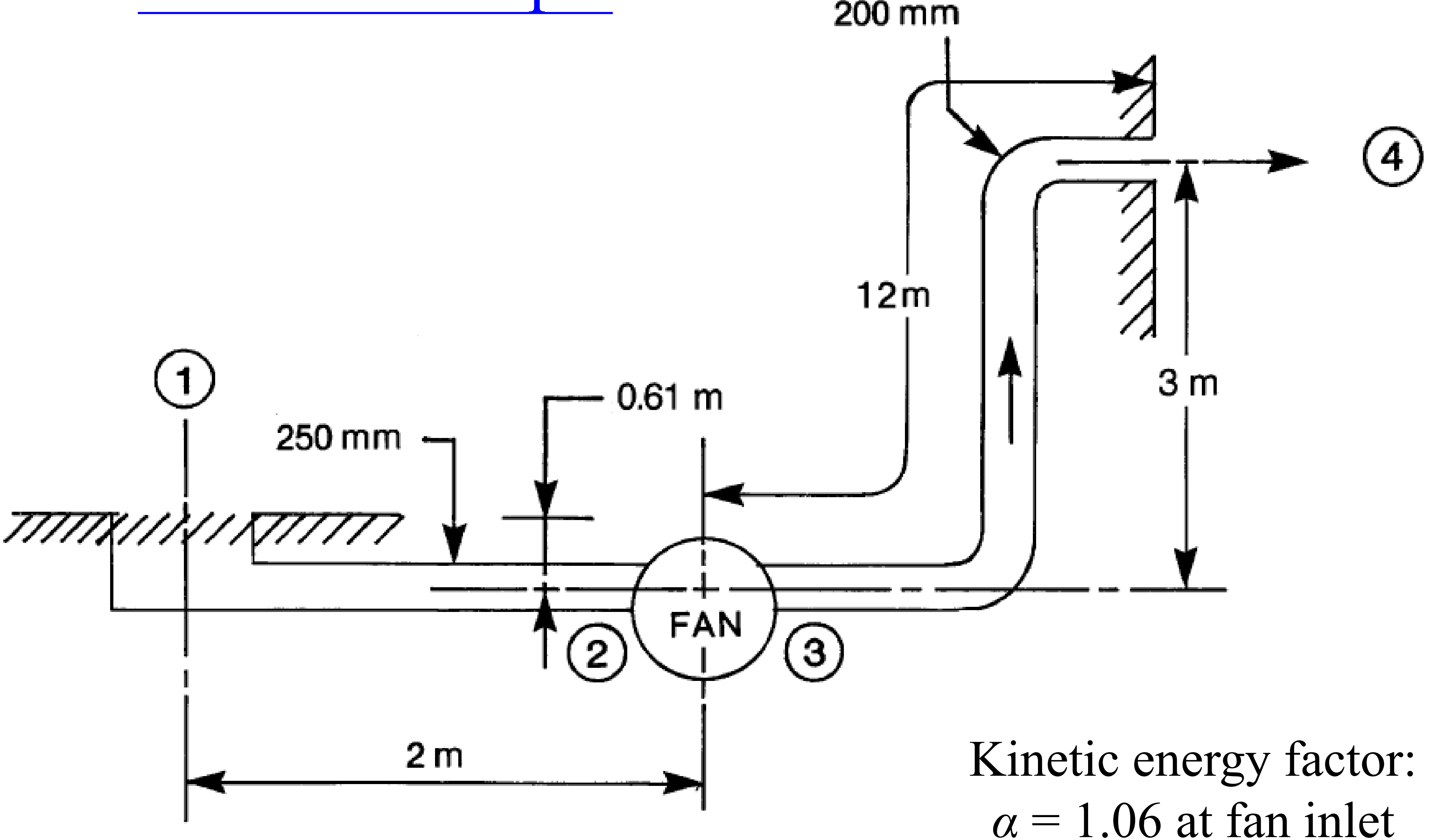
- Aims
  - To correlate pressure changes with flow rates and nature of the conduit
  - To evaluate flow rate and specify pump/fan for a conduit piping system
- Generalised Bernoulli Equation

$$\left(\frac{p}{\rho g}+\alpha\frac{V^2}{2g}+z\right)_1+H_M=\left(\frac{p}{\rho g}+\alpha\frac{V^2}{2g}+z\right)_2+H_L$$

Flow Analysis

- Worked Example:
  - Specify the fan to produce an isothermal airflow of 200 L/s through the ducting system. Accounting for intake and fitting losses, the equivalent conduit lengths are 18 and 50 m and the flow is isothermal. The pressure at the inlet (station 1) and following the discharge (station 4), where the velocity is zero, are the same. Friction losses H_L are evaluated as 7.5 m of air between stations 1 and 2, and 72.3 m between stations 3 and 4.

Worked Example



Kinetic energy factor:
$\alpha = 1.06$ at fan inlet
$\alpha = 1.03$ at fan outlet

(Source: *ASHRAE Fundamentals Handbook 2001*)

Flow Analysis

- Apply Bernoulli equation to stations 1 & 4
  - The pressure terms are the same; velocity is zero
  - $(p/\rho g)+0+0.61+H_M = (p/\rho g)+0+3+(7.5+72.3)$
  - Therefore, $H_M = 82.2$ m of air = required fan pressure
- Alternatively, H_M can be determined from stations 2 & 3, but some more steps are needed, as shown in the followings

Flow Analysis

- Calculate the kinetic terms at fan inlet/outlet:
  - $A_2 = \pi(D/2)^2 = \pi(0.25/2)^2 = 0.0491\ \mathrm{m}^2$
  - $V_2 = Q / A_2 = 0.2 / 0.0491 = 4.07\ \mathrm{m/s}$
  - For fan inlet, $V_2^2/2g = (4.07)^2 / 2(9.8) = 0.846\ \mathrm{m}$
  - Similarly for fan outlet, $V_3^2/2g = 2.07\ \mathrm{m}$
- Apply Bernoulli to stations 1 & 2 and 3 & 4
  - $(p_1/\rho g)+0+0.61+0=(p_2/\rho g)+(1.06\mathrm{x}0.846)+0+7.5$
  - $(p_3/\rho g)+(1.03\mathrm{x}2.07)+0+0=(p_4/\rho g)+0+3+72.3$

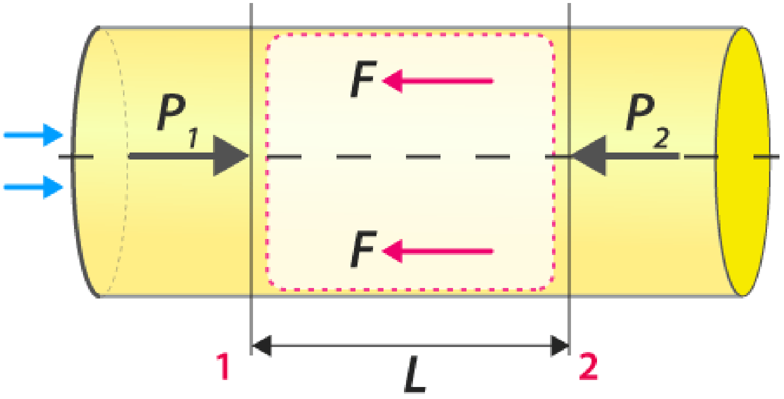
Flow Analysis

- Therefore,
  - $(p_2/\rho g)-(p_1/\rho g) = -7.8$ m of air
  - $(p_3/\rho g)-(p_4/\rho g) = 73.2$ m of air
- Apply Bernoulli to stations 2 & 3 and knowing $p_1 = p_4 =$ zero gauge, therefore,
  - $H_M = 73.2 + (1.03\text{x}2.07) - [-7.8 + (1.06\text{x}0.846)] = 75.3 - (-6.9) = 82.2$ m of air

Flow Analysis

- Conduit friction
  - Frictional shear at bounding walls
  - Flow energy is converted into heat (fluid internal energy), unrecoverable (a loss)
  - This loss can be evaluated by Darcy-Weishbach Equation:

$$(H_L)_f = f\left(\frac{L}{D}\right)\left(\frac{V^2}{2g}\right)$$



    - L = length of conduit
    - D = diameter
    - f = friction factor (for turbulent flow, f = 0.01 to 0.05)

Flow Analysis

- For fully-developed laminar flow in a pipe,

$$(H_L)_f = \frac{L}{\rho g}\left(\frac{8\mu V}{R^2}\right) = \frac{32 L \nu V}{D^2 g} = \frac{64}{VD/\nu}\left(\frac{L}{D}\right)\left(\frac{V^2}{2g}\right)$$

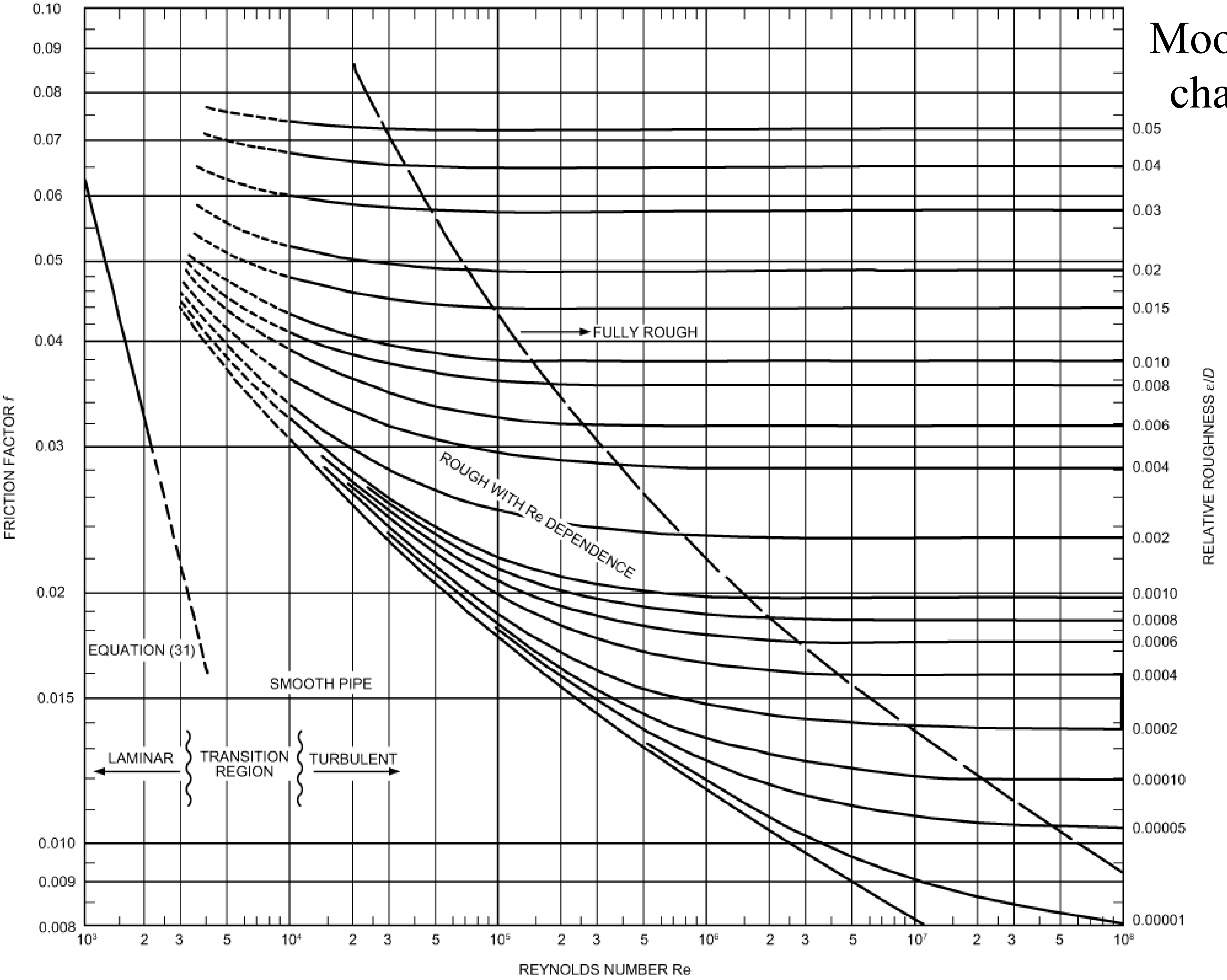
  - Where Re = VD/ν and $f = 64$ / Re
  - Friction factor varies inversely with Re
- With turbulent flow, friction loss depends also on nature of conduit wall surface

(See also: Darcy-Weisbach Pipe Friction Loss Calculator https://www.lmnoeng.com/darcy.php)

Flow Analysis

- For smooth conduit walls, empirically,
  - $f = 0.3164 / \mathrm{Re}^{0.25}$ for $\mathrm{Re} < 10^5$
  - $f = 0.0032 + 0.221 / \mathrm{Re}^{0.237}$ for $10^5 < \mathrm{Re} < 3 \times 10^6$
- f also depends on wall roughness ε and can be studied using a "Moody chart"
  - For high Re and ε, friction factor is independent of Re in a fully-rough flow regime, then
    - $1/\sqrt{f} = 1.14 + 2 \log (D/\varepsilon)$

Moody chart



(Source: *ASHRAE Fundamentals Handbook 2005*)

Flow Analysis

- Between smooth tubes and fully-rough regime, friction factor can be represented by Colebrook's natural roughness function:

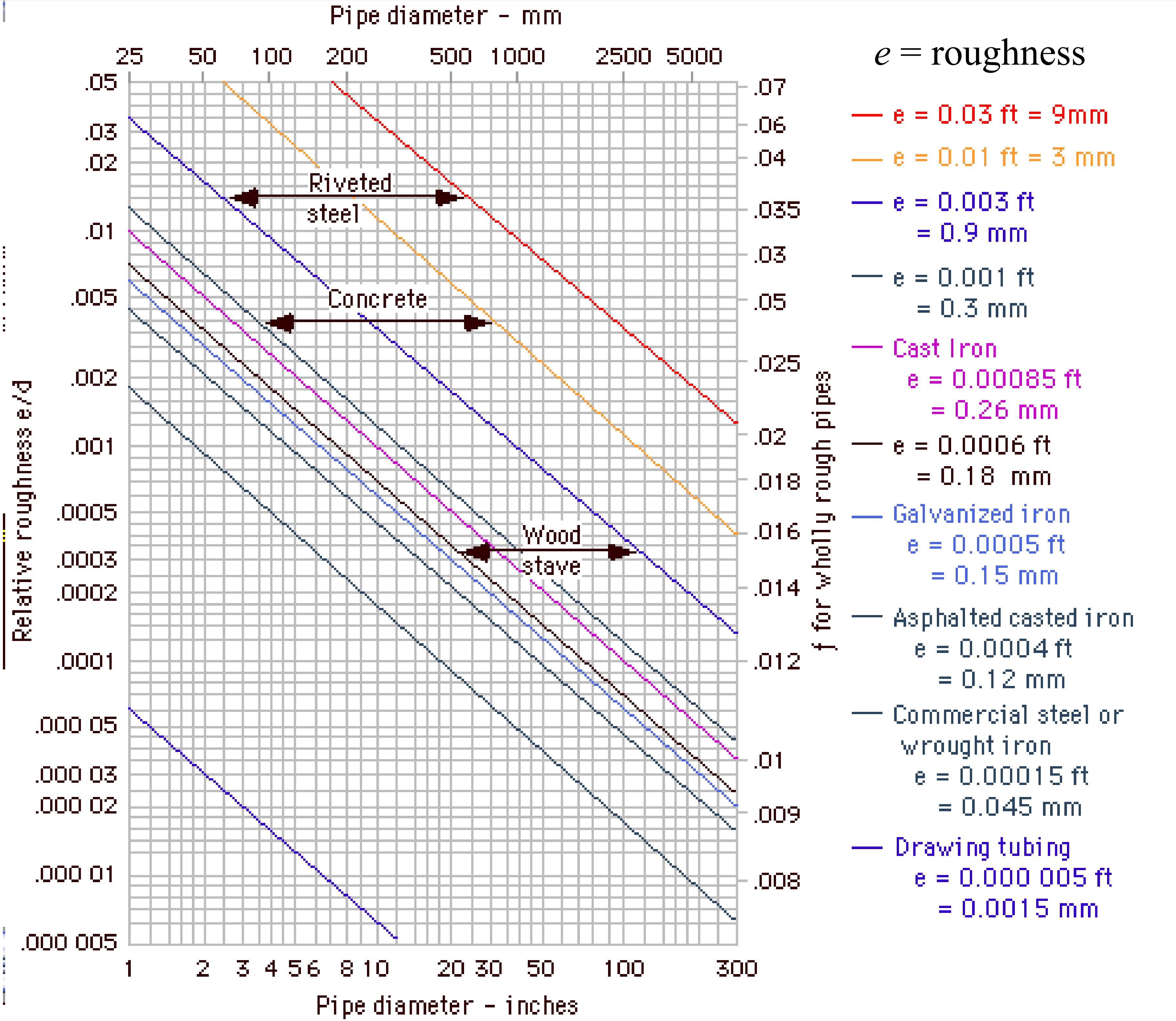
$$\frac{1}{\sqrt{f}} = 1.14 + 2\log(D/\varepsilon) - 2\log\left[1 + \frac{9.3}{\mathrm{Re}(\varepsilon/D)\sqrt{f}}\right]$$

- Transition region: 2000 < Re < 10000
- For smooth wall,
  - Laminar: Re < 2000, *f* = 64/Re
  - If Re > 10000, the empirical equations are used

Flow Analysis

- For rough walls, Moody chart and Colebrook function are used to assess friction factor in turbulent flow
- The roughness height will be evaluated from the conduit surface (found from Table)
- For rectangular air duct, the circular equivalent can be calculated using $D_{\mathrm{eq}} = 4A / P_w$
  - A = flow area; P_w = wetted perimeter of cross section

Pipe sizing chart



Further Reading

- ASHRAE, 2021. *ASHRAE Handbook Fundamentals 2021*, Chp. 3 - Fluid Flow, American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc., Atlanta, GA.
- Darcy-Weisbach equation - Wikipedia
  - https://en.wikipedia.org/wiki/Darcy%E2%80%93Weisbach_equation
- Engineering ToolBox:
  - Moody Diagram https://www.engineeringtoolbox.com/moody-diagram-d_618.html
  - Colebrook Equation https://www.engineeringtoolbox.com/colebrook-equation-d_1031.html