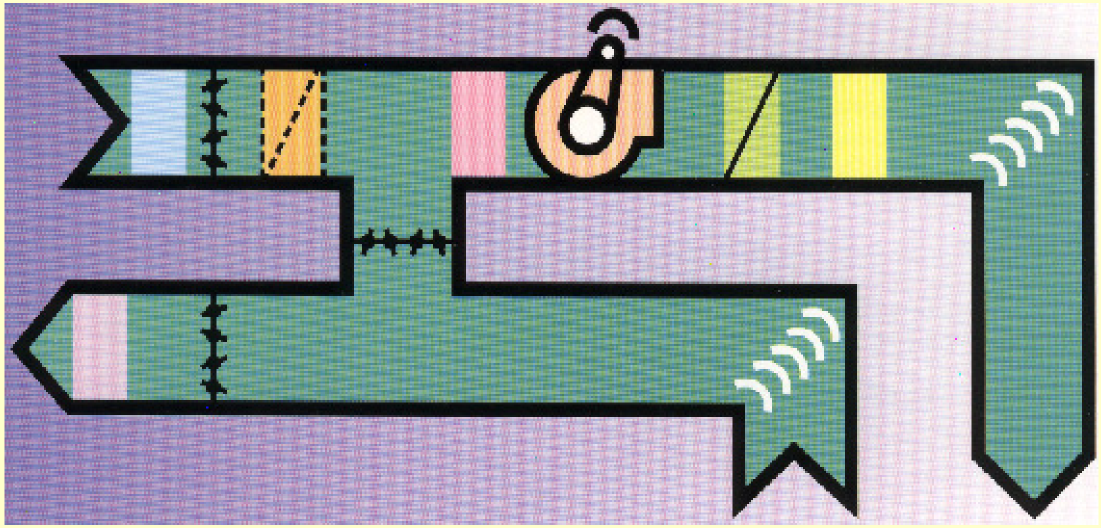


HVAC Air-side Systems: Part 2 Air Duct Design and Space Air Diffusion

Dr. Sam C. M. Hui
Department of Mechanical Engineering
The University of Hong Kong
E-mail: cmhui@hku.hk

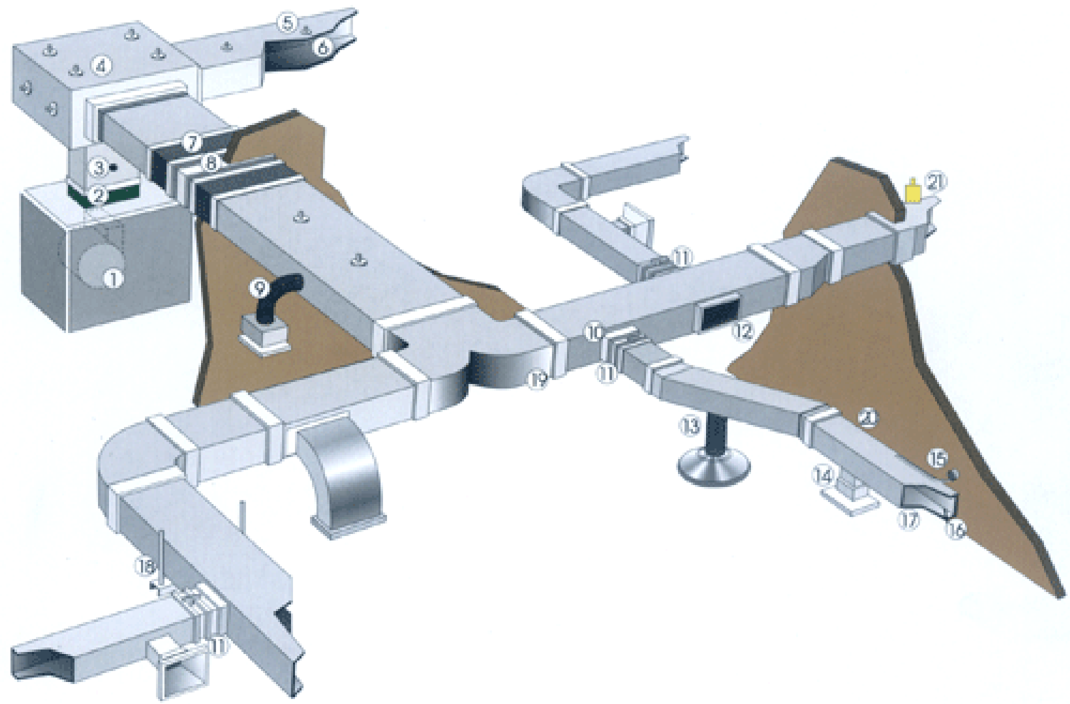
Jan 2016

Contents

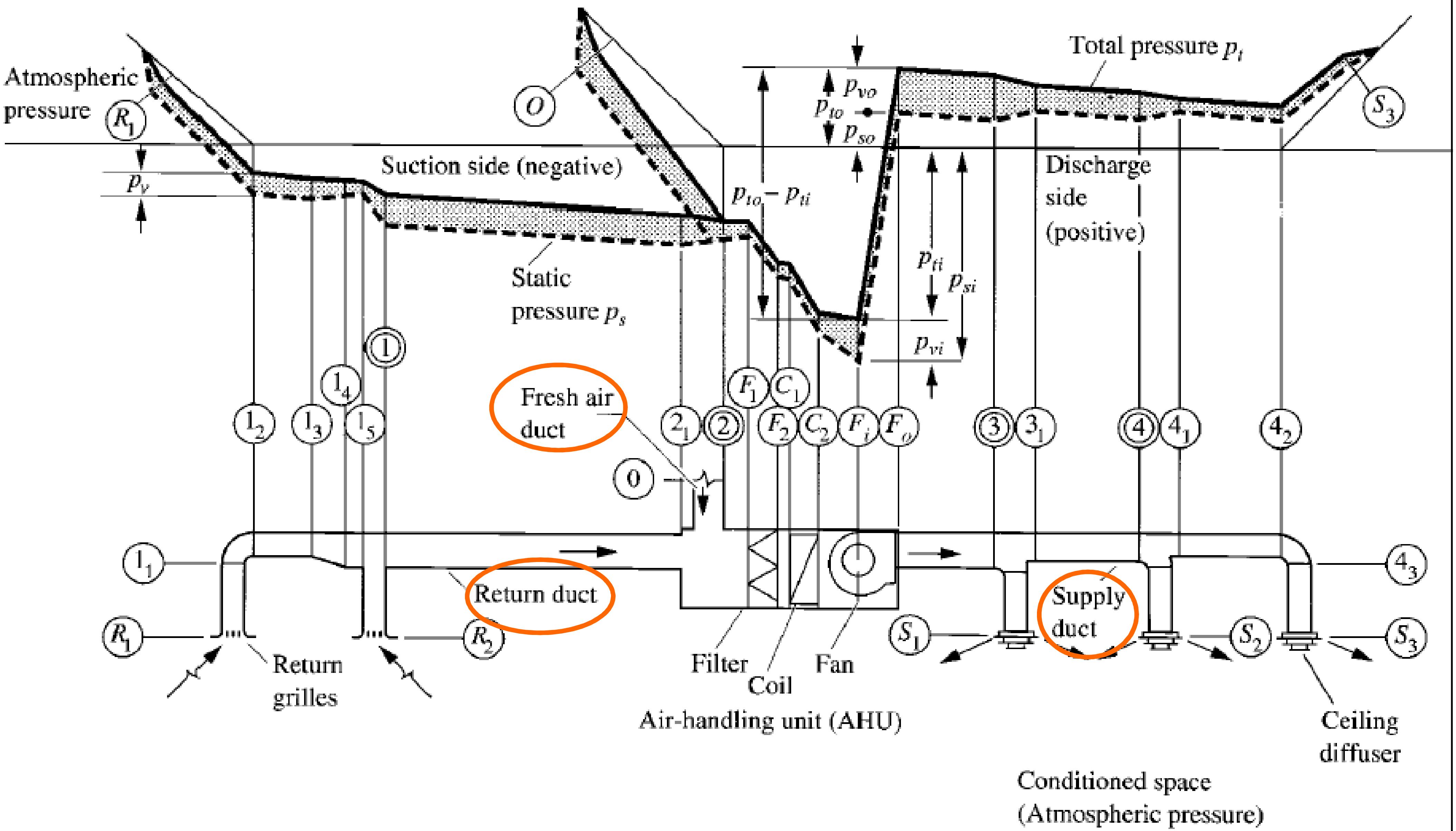
- Duct Construction
- Duct Properties
- Air Duct Design and Sizing
- Space Air Diffusion
- Air Jets
- Outlets and Inlets

Duct Construction

- Types of air duct
  - Supply air duct
  - Return air duct
  - Outdoor air duct
  - Exhaust air
- Duct sections
  - Header or main duct (trunk)
  - Branch duct or runout



Pressure characteristics of HVAC air duct system



[Source: Kreider, K. F. (ed.), 2001. *Handbook of Heating, Ventilation, and Air Conditioning*, CRC Press, Boca Raton, FL.]

Duct Construction

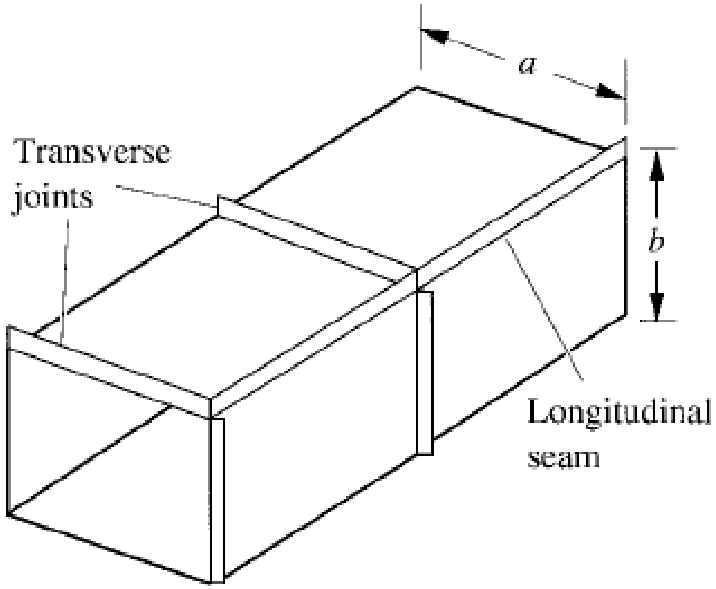
- Materials of air duct
  - Galvanized steel (sheet metal)
  - Aluminium
  - Polyurethane and phenolic insulation panels (pre-insulated air ducts)
  - Fiberglass duct board (preinsulated non-metallic ductwork)
  - Flexible ducting
  - Fabric air duct

(See also: Duct (flow) -- Wikipedia http://en.wikipedia.org/wiki/Duct_(flow))

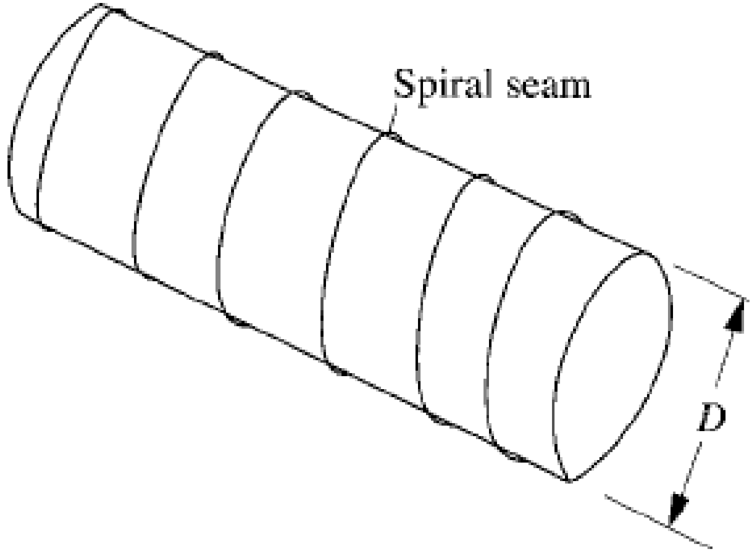
Duct Construction

- Duct systems
  - Max. pressure difference (between air inside the duct and the ambient air)
    - 125, 250, 500, 750, 1000, 1500, 2500 Pa
  - Commercial buildings
    - Low-pressure duct system: $\leq$ 500 Pa, max 12 m/s
    - Medium-pressure system: 500-1500 Pa, max 17.5 m/s
  - Residential buildings: 125 Pa or 250 Pa
  - Industrial duct system: ΔP can be higher

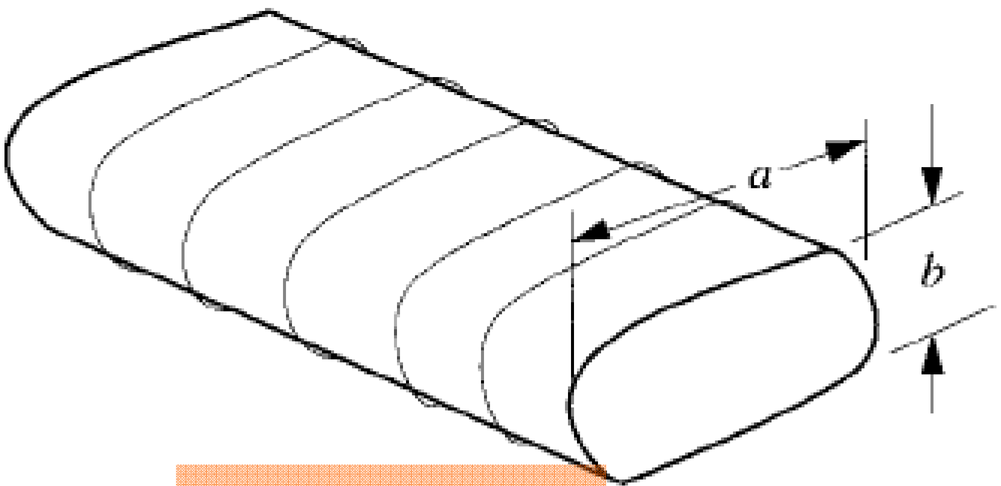
Different types of air ducts



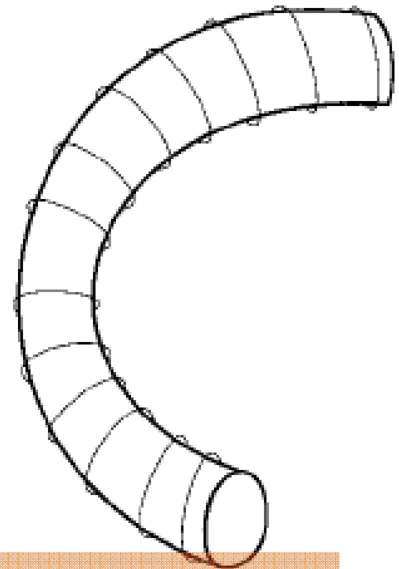
Rectangular duct



Round duct w/ spiral seam



Flat oval duct



Flexible duct

(Source: *Wang, S. K., 2001. Handbook of Air Conditioning and Refrigeration*)

Duct Construction

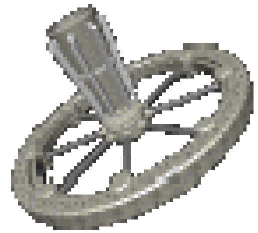
- Duct specification
  - Sheet gauge and thickness of duct material
  - Traverse joints & longitudinal seam reinforcements
  - Duct hangers & their spacing
  - Tapes & adhesive closures
  - Fire spread and smoke developed
  - Site-fabricated or factory-fabricated

Do you know how to specify or check the air duct installation?

Duct Construction

- Duct heat gain or loss
  - Temperature rise or drop
  - Duct insulation (mounted or inner-lined)
    - Reduce heat gain/loss, prevent condensation, sound attenuation
    - Minimum & recommended thickness
      - ASHRAE standard or local codes
  - Temperature rise of the air
    - Depends on air velocity, duct dimensions & insulation

Duct Properties



- Frictional losses: Darcey-Weisbach Equation
  - H_f = friction head loss, or Δp_f = pressure loss

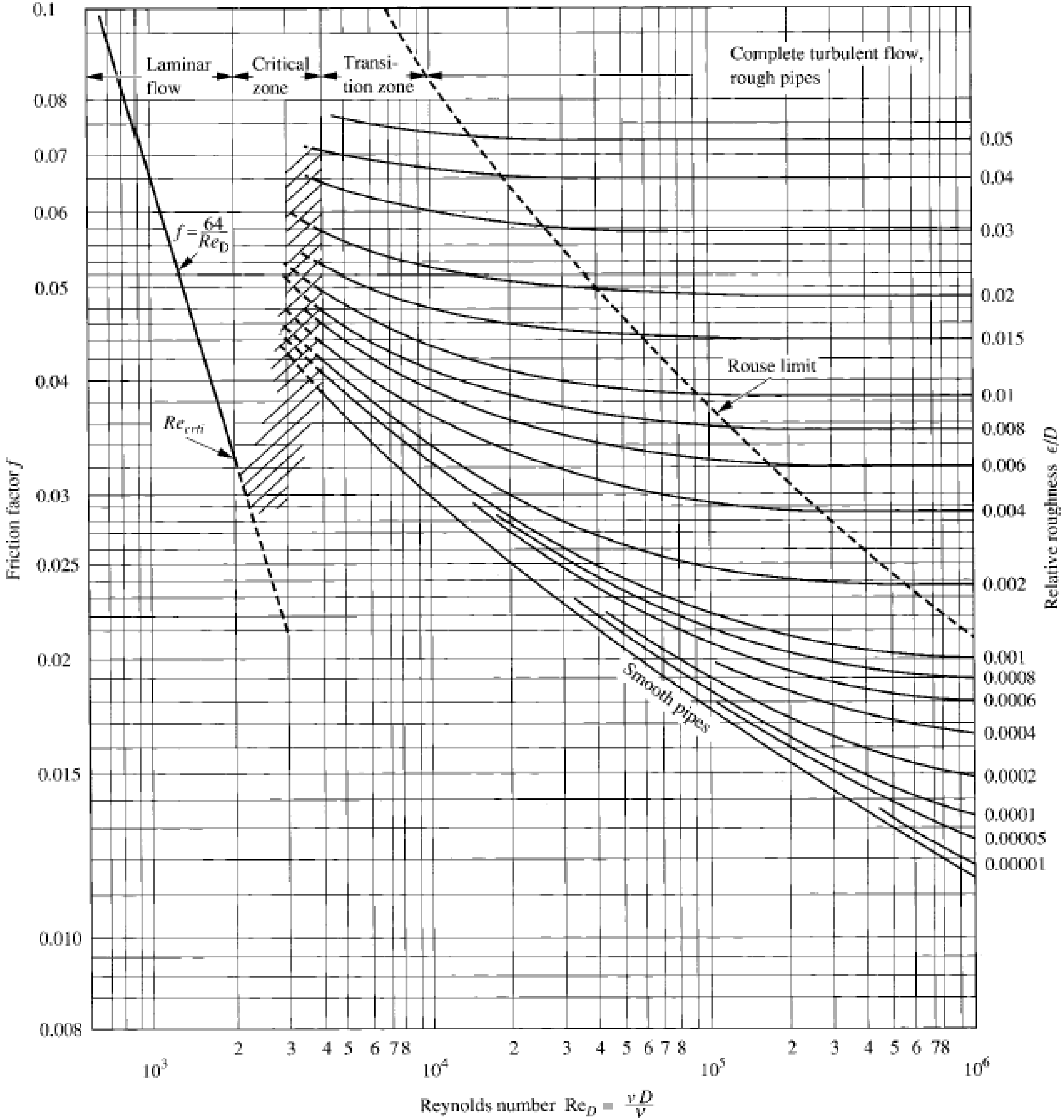
$$H_f = f\left(\frac{L}{D}\right)\left(\frac{v^2}{2g}\right) \qquad \Delta p_f = f\left(\frac{L}{D}\right)\left(\frac{\rho v^2}{2g_c}\right)$$

    - f = friction factor (dimensionless)
    - L = length of duct or pipe (m)
    - D = diameter of duct or pipe (m)
    - v = mean air velocity in duct (m/s)
    - g = gravitational constant (m/s^2)
    - ρ = density of fluid (kg/m^3)
    - g_c = dimensional constant, for SI unit, $g_c = 1$

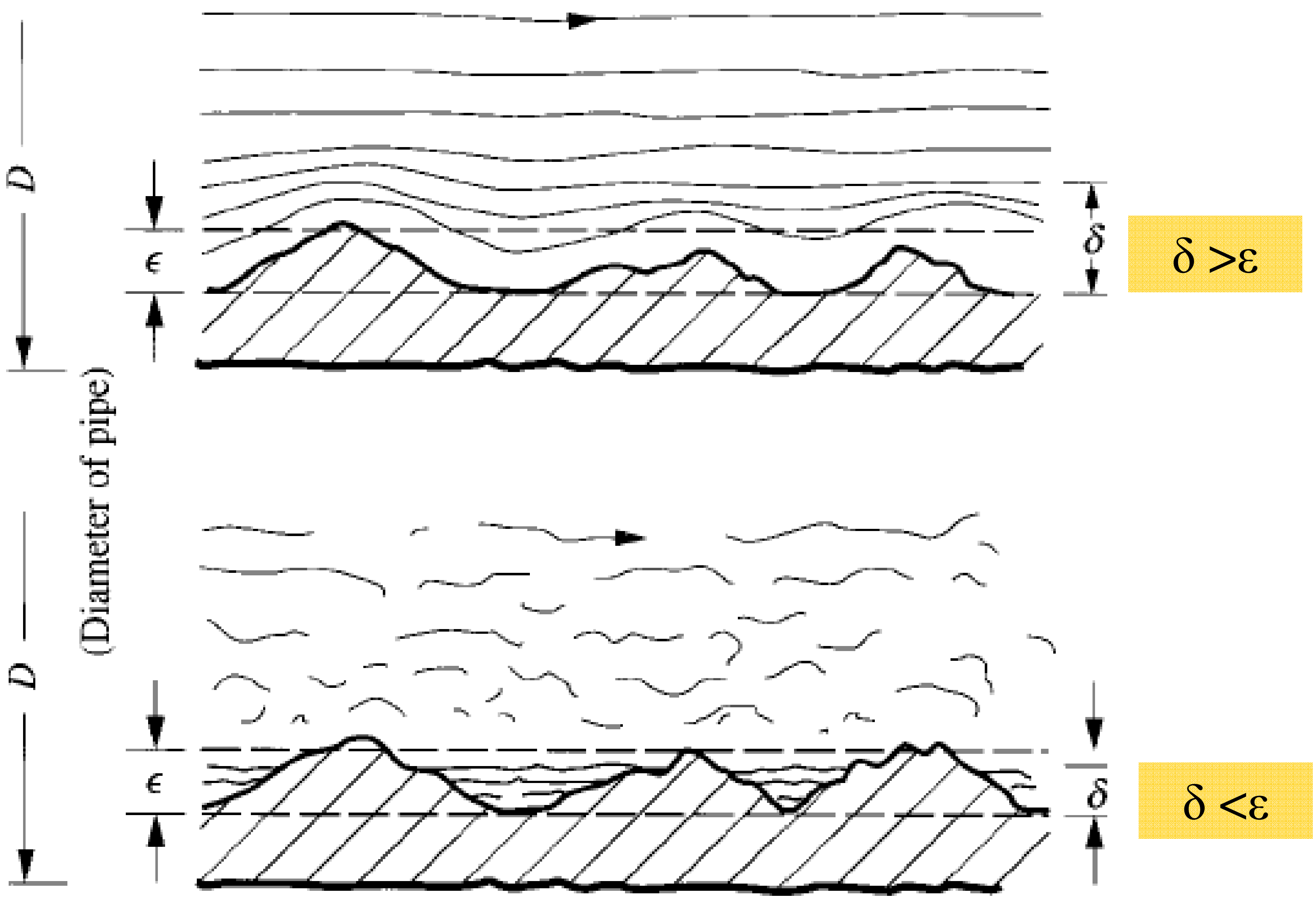
Duct Properties

- Frictional losses
  - Friction factor (*f*)
    - Re_D (Reynolds number)
    - ε= absolute roughness; ε/ D = relative roughness
    - Smooth duct & rough duct
  - Moody diagram
    - Laminar flow ($Re_D < 2000$), $f = 64 / Re_D$
    - Critical & transition zone
    - Turbulent flow: Rouse limit, $Re_D = 200 / \sqrt{[f\,(\varepsilon / D)]}$

Moody diagram



Mode of airflow when air passes over and around surface protuberances of the duct wall

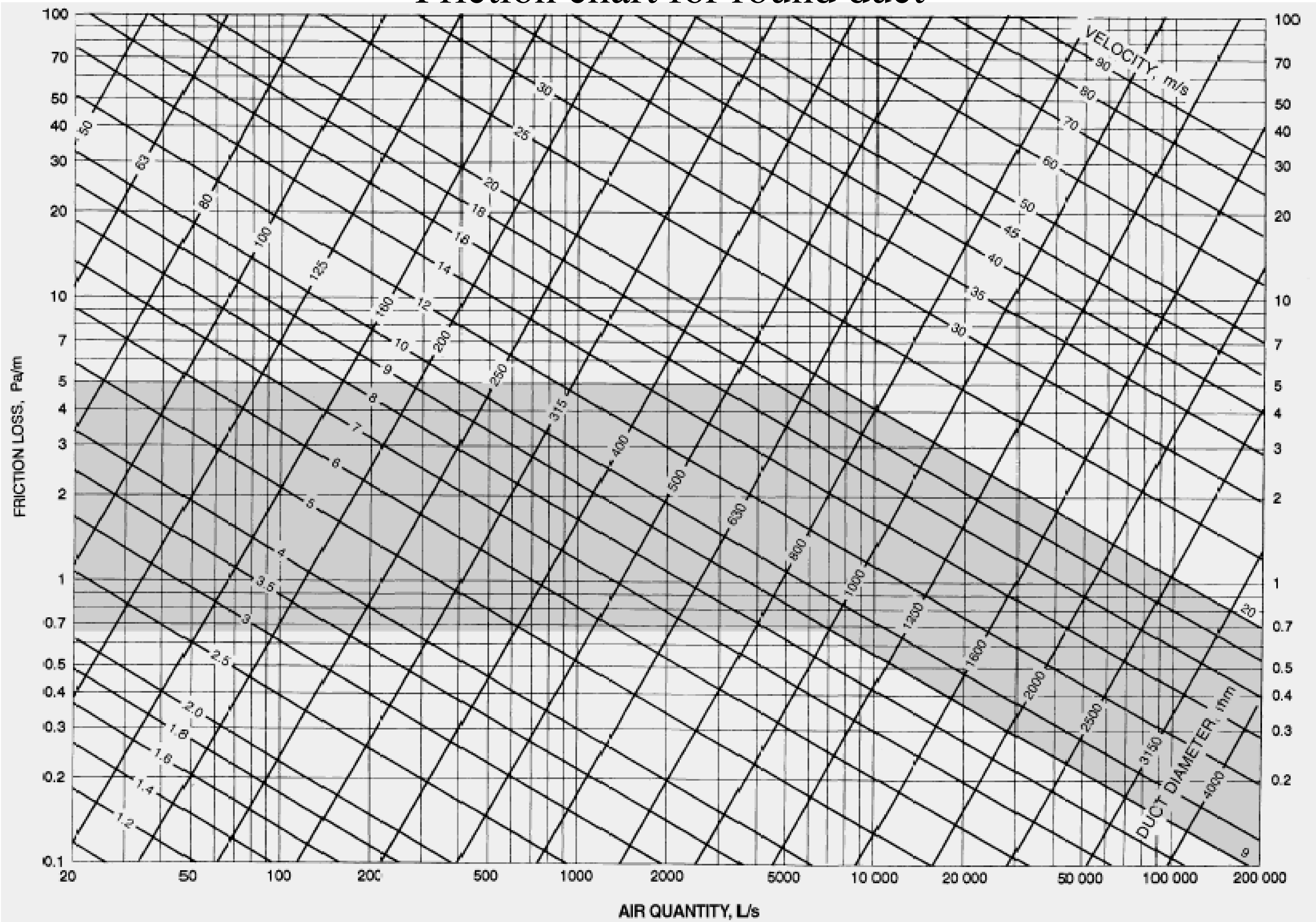


(Source: *Wang, S. K., 2001. Handbook of Air Conditioning and Refrigeration*)

Duct Properties

- Duct friction chart
  - Colebrook formula $$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon}{3.7D} + \frac{2.51}{\mathrm{Re}_D\sqrt{f}}\right)$$
- Roughness & temperature corrections
  - $\Delta p_f = K_{\mathrm{sr}}\, K_T\, K_{\mathrm{el}} \Delta p_{f,c}$
    - K_{sr} = correction factor for surface roughness
    - K_T = correction factor for air temperature
    - K_{el} = correction factor for elevation

Friction chart for round duct



(Source: *ASHRAE Handbook Fundamentals 2001*)

Duct Properties

- Circular equivalent
  - Hydraulic diameter, $D_h = 4\ A\ /\ P$
    - A = area (mm^2); P = perimeter (mm)
  - Rectangular duct:

$$D_e = \frac{1.30(ab)^{0.625}}{(a+b)^{0.25}}$$

  - Flat oval duct:

$$D_e = \frac{1.55A^{0.625}}{P^{0.25}}$$

$$A = \frac{\pi b^2}{4} + b(a-b)$$

$$P = \pi b + 2(a+b)$$

Duct Properties

- Dynamic losses
  - Result from flow disturbances caused by duct-mounted equipment and fittings
    - Change airflow path's direction and/or area
    - Flow separation & eddies/disturbances
  - In dynamic similarity (same Reynolds number & geometrically similar duct fittings), dynamic loss is proportional to their velocity pressure

Duct Properties

- Local or dynamic loss coefficient
  - Ratio of total pressure loss to velocity pressure

$$C = \frac{\Delta p_j}{(\rho V^2/2)} = \frac{\Delta p_j}{p_v}$$

where

C = local loss coefficient, dimensionless

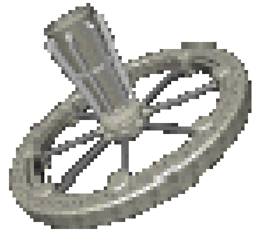
Δp_j = total pressure loss, Pa

ρ = density, kg/m^3

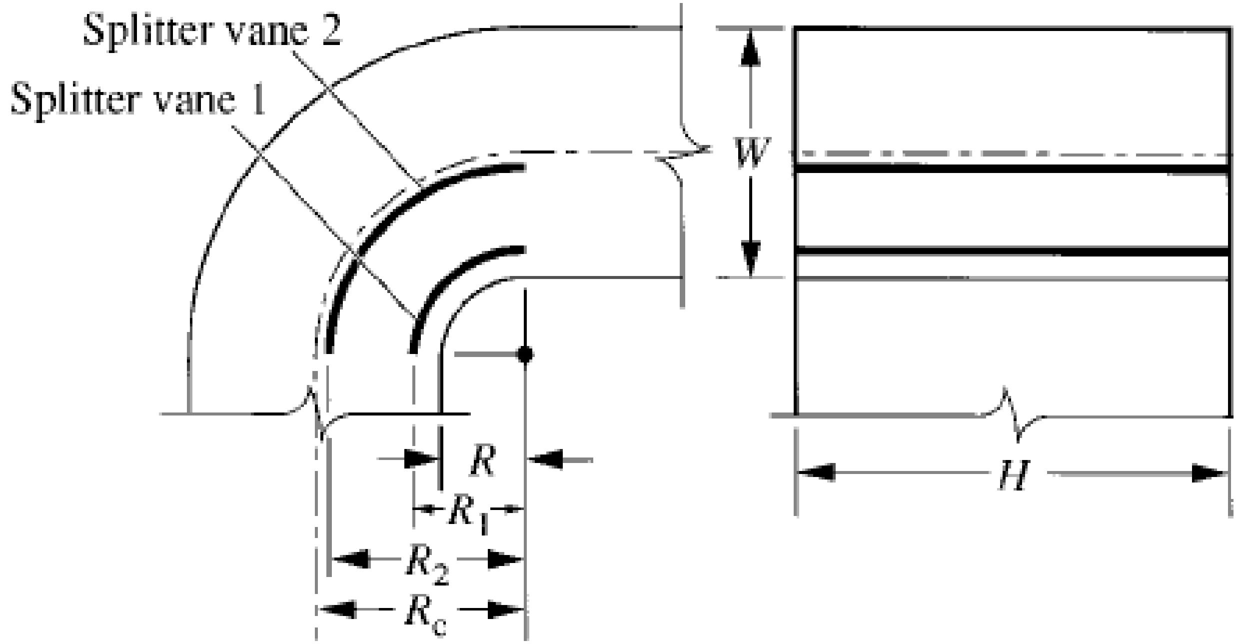
V = velocity, m/s

p_v = velocity pressure, Pa

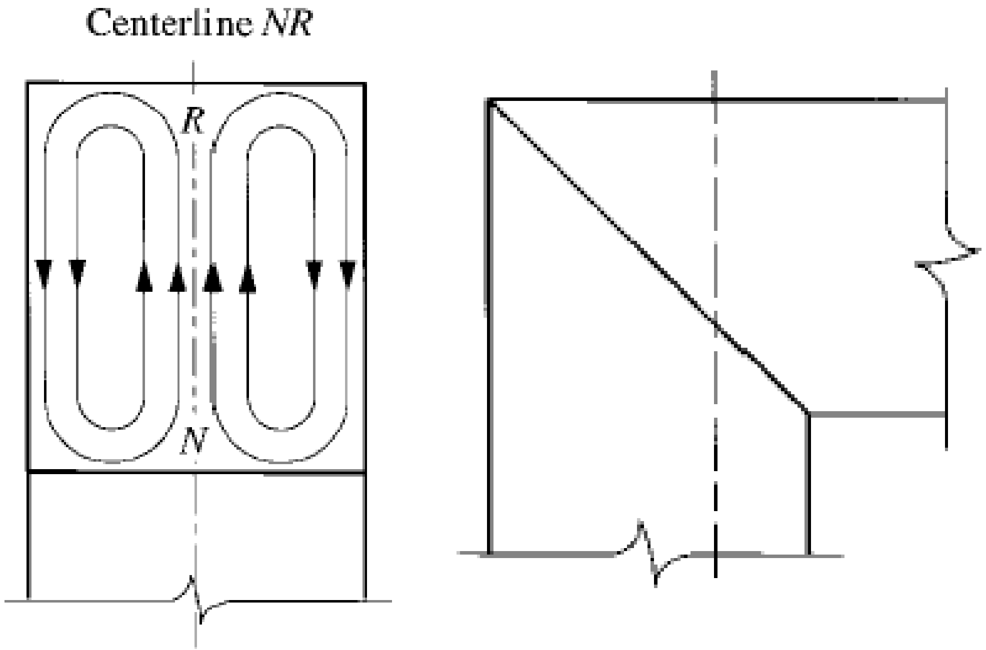
Duct Properties

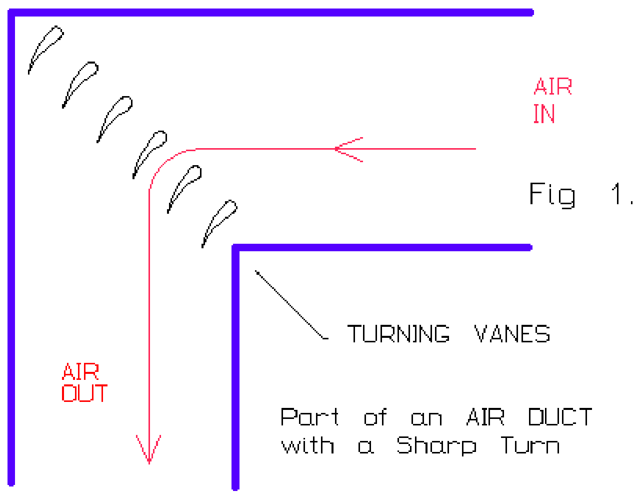


- Duct fittings
  - Elbows
  - Converging or diverging tees and wyes
  - Entrances and exits
  - Enlargements and contractions
- Means to reduce dynamic losses
  - Turning angle, splitter vanes
- ASHRAE duct fitting database
  - Fitting loss coefficients



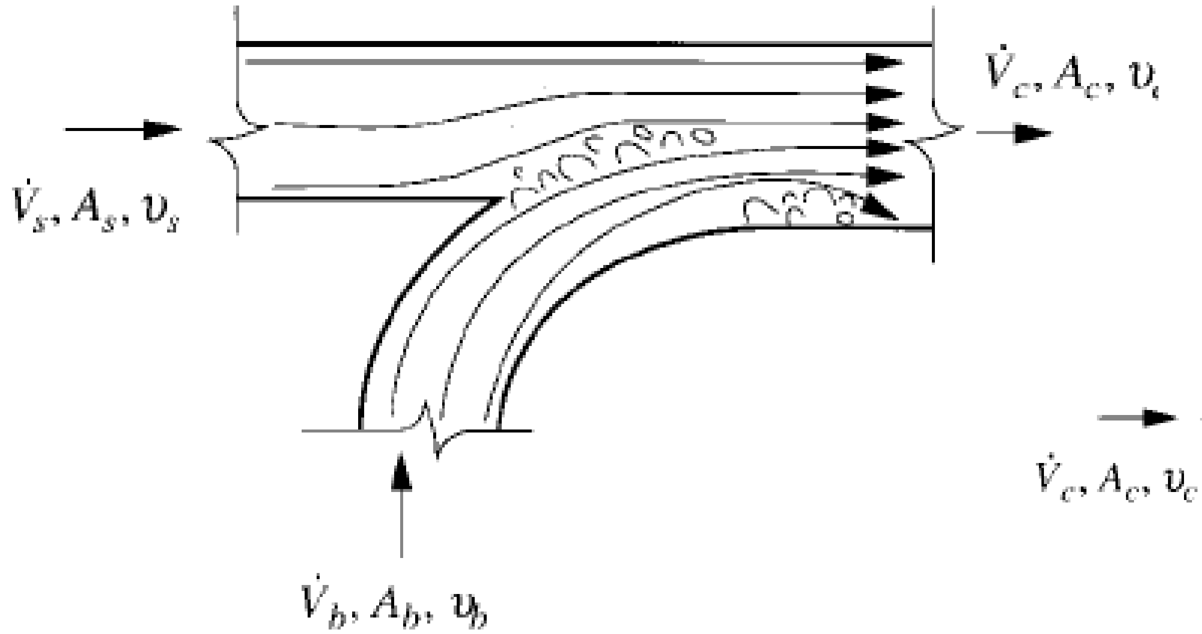
Rectangular elbow, smooth radius, 2 splitter vanes

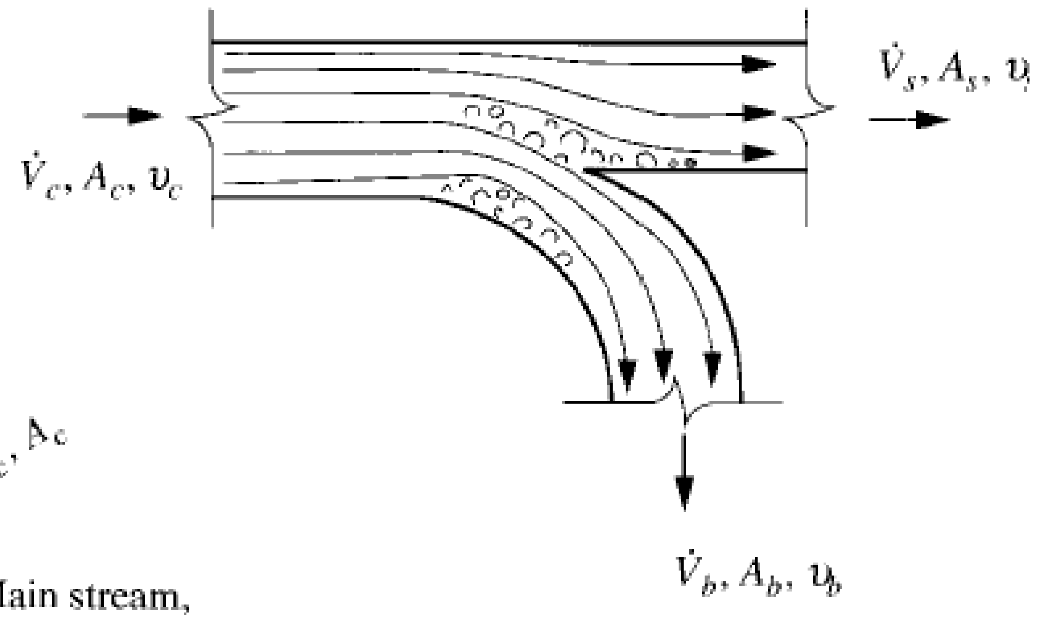


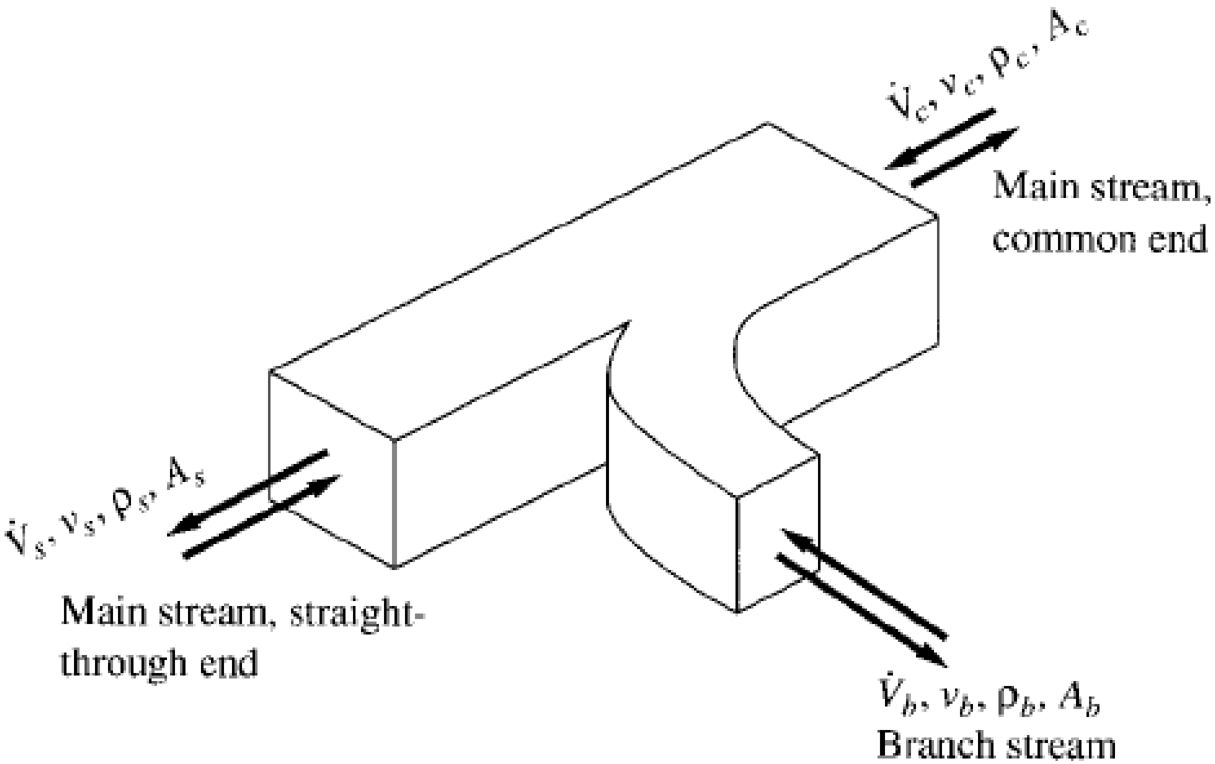


Mitered elbow and its secondary flow

(Source: *ASHRAE Handbook Fundamentals 2001*)

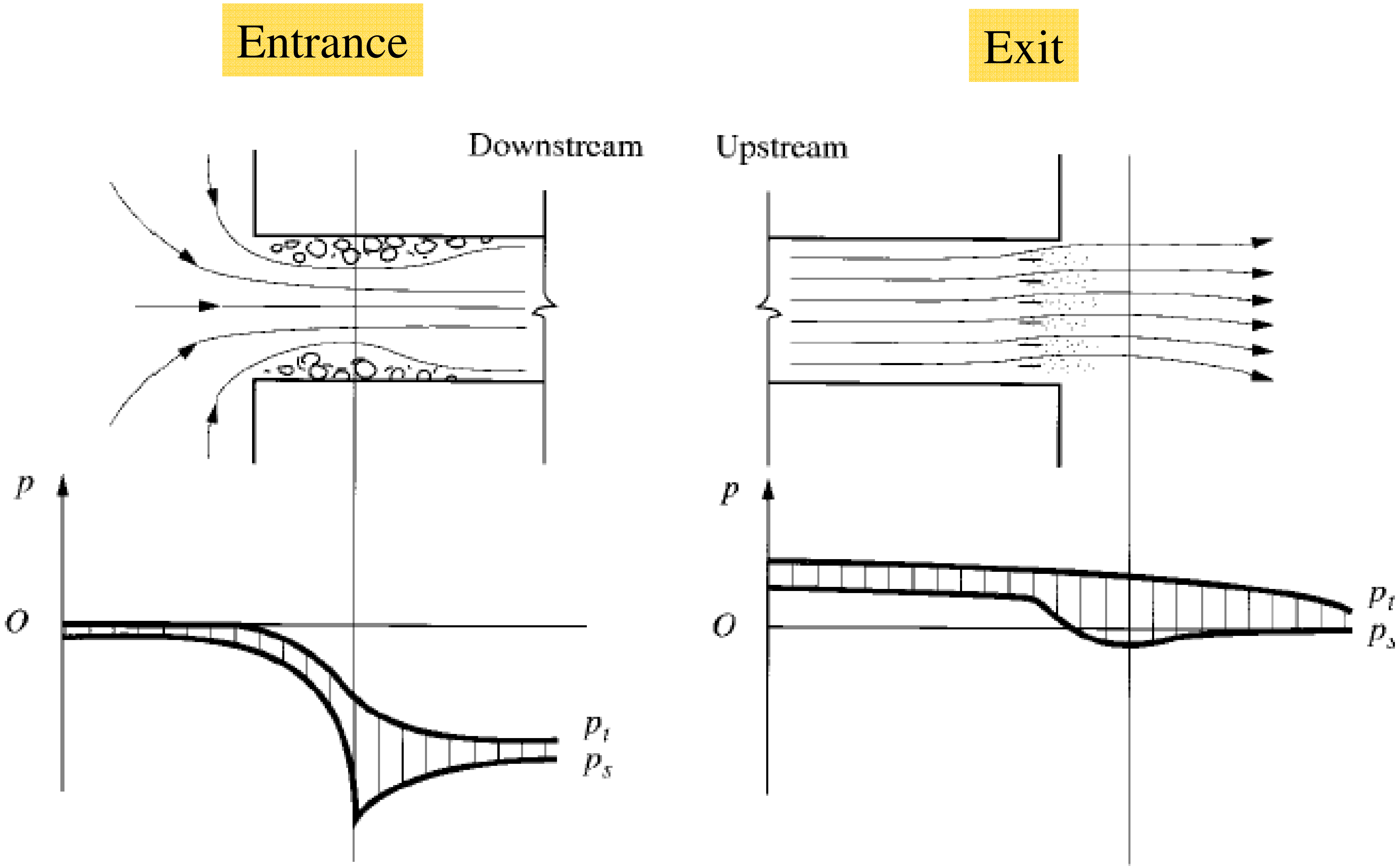






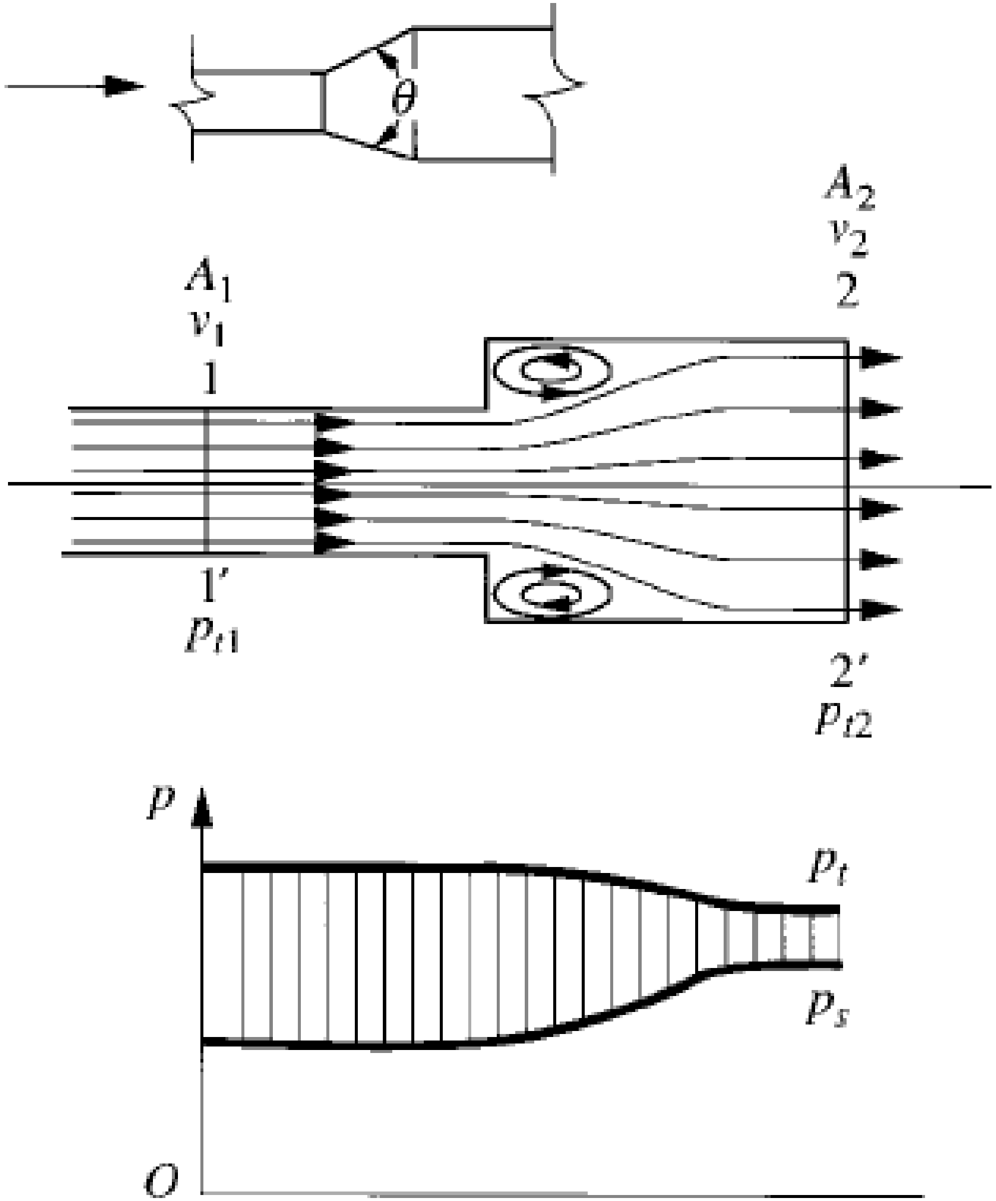
Airflow through a rectangular converging or diverging wye

(Source: *Wang, S. K., 2001. Handbook of Air Conditioning and Refrigeration*)

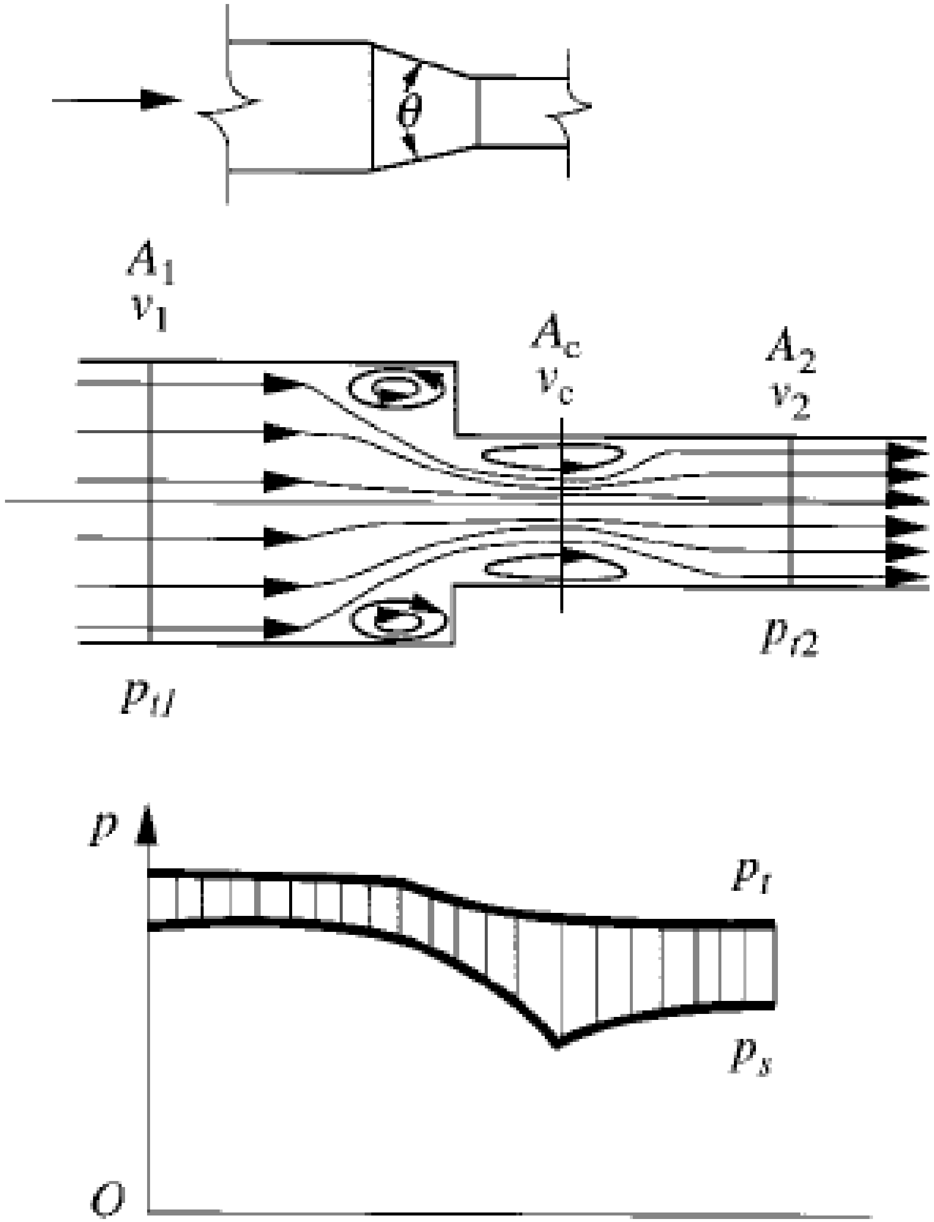


(Source: *Wang, S. K., 2001. Handbook of Air Conditioning and Refrigeration*)

Abrupt enlargement

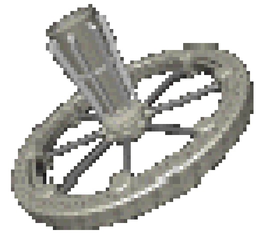


Sudden contraction



(Source: *Wang, S. K., 2001. Handbook of Air Conditioning and Refrigeration*)

Duct Properties

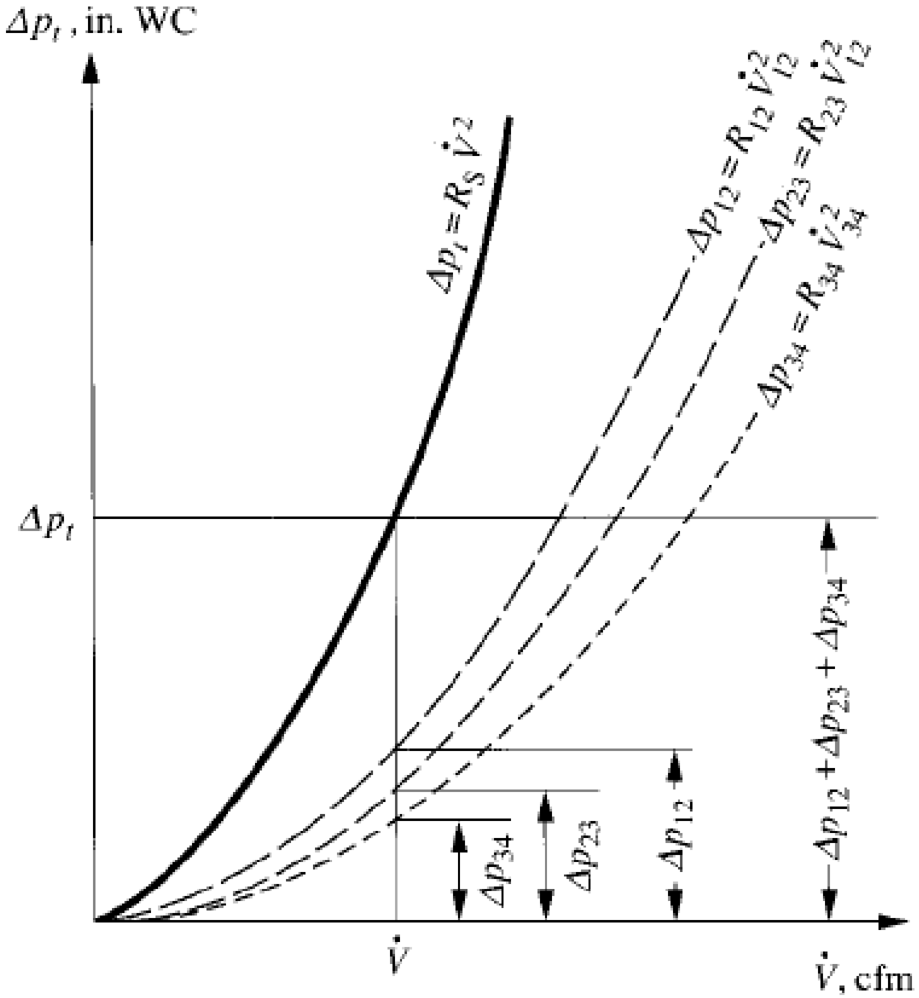


- Flow resistance, R
  - Total pressure loss Δp_t at a specific volume flow rate V

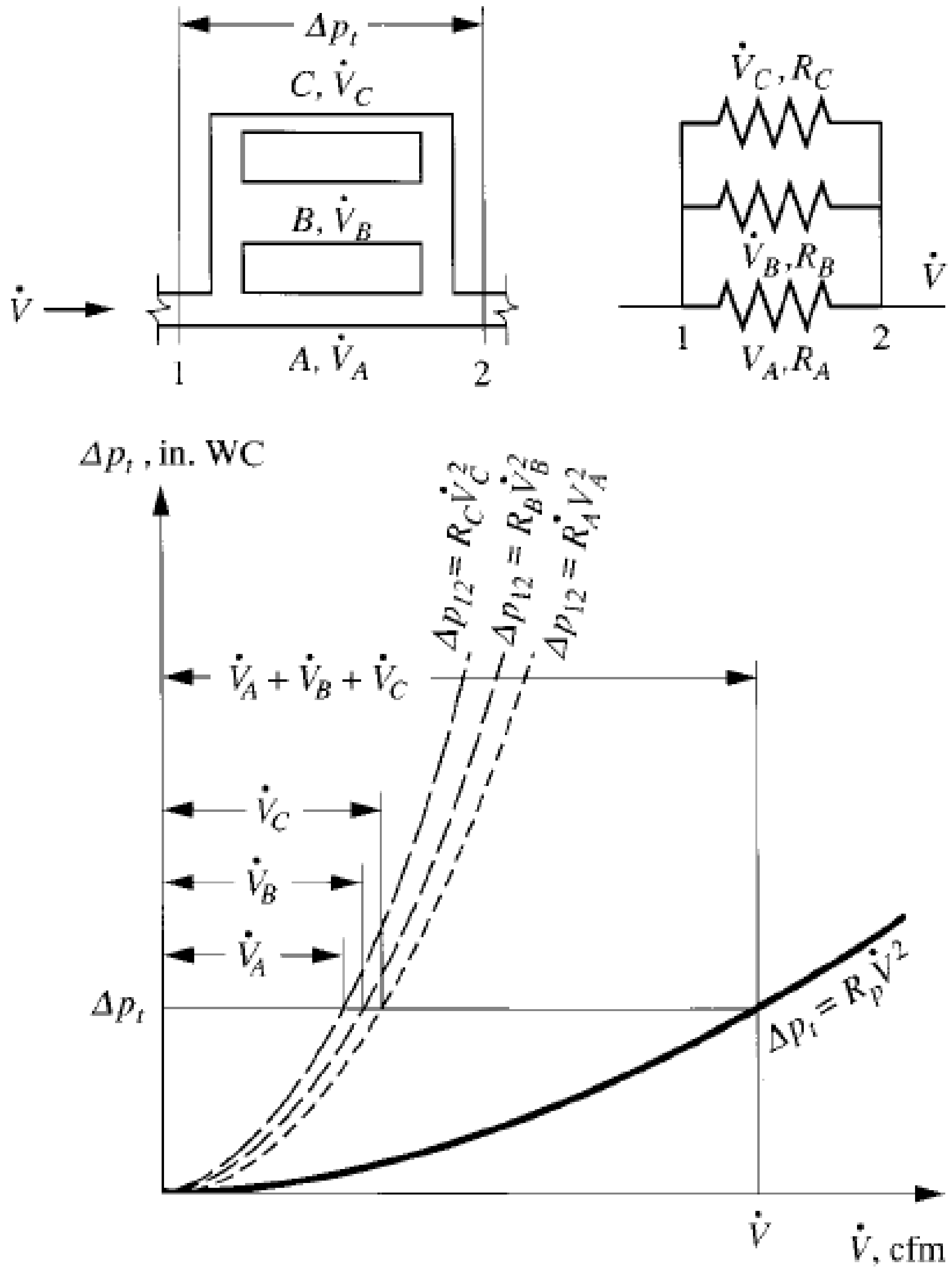
$$\Delta p_t = R \cdot \dot{V}^2$$

  - Flow resistance in series: $R_s = R_1 + R_2 + \ldots + R_n$
  - Flow resistance in parallel:

$$\frac{1}{\sqrt{R_p}} = \frac{1}{\sqrt{R_1}} + \frac{1}{\sqrt{R_2}} + \ldots + \frac{1}{\sqrt{R_n}}$$



Flow resistance in series

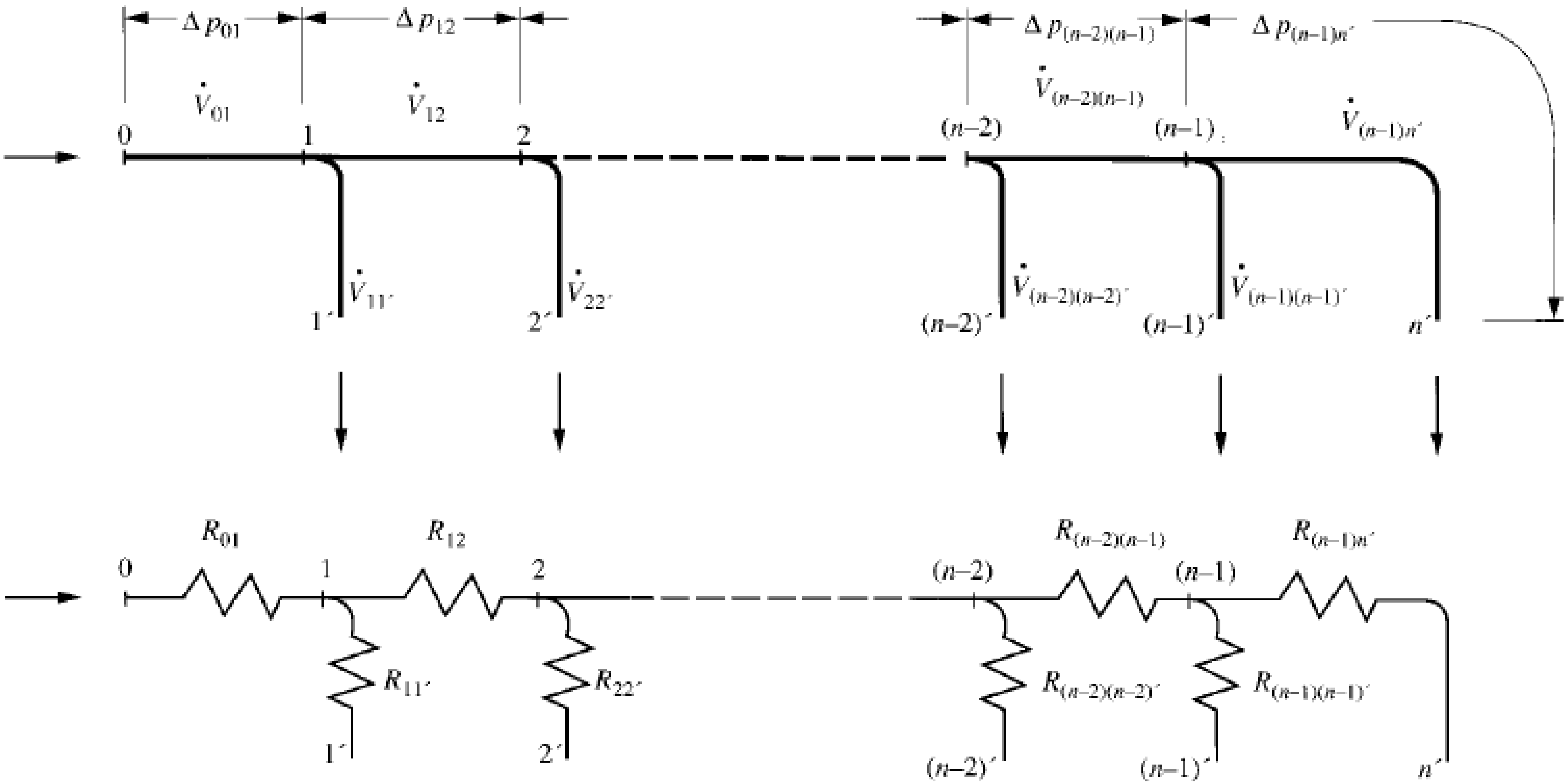


Flow resistance in parallel

(Source: *Wang, S. K., 2001. Handbook of Air Conditioning and Refrigeration*)

Air Duct Design & Sizing

- Optimal air duct design
  - Optimal duct system layout, space available
  - Satisfactory system balance
  - Acceptable sound level
  - Optimum energy loss and initial cost
  - Install only necessary balancing devices (dampers)
  - Fire codes, duct construction & insulation
- Require comprehensive analysis & care for different transport functions



Flow characteristics of a supply duct system

(Source: *Wang, S. K., 2001. Handbook of Air Conditioning and Refrigeration*)

Air Duct Design & Sizing

- Design velocity
  - Constraints: space available, beam depth
  - Typical guidelines:
    - Main ducts: air flow usually ≤ 15 m/s; air flow noise must be checked
    - With more demanding noise criteria (e.g. hotels), max. air velocity: main duct ≤ 10-12.5 m/s, return main duct ≤ 8 m/s, branch ducts ≤ 6 m/s
  - Face velocities for air-handling system components

Air Duct Design & Sizing

- System balancing
  - Air volume flow rate meeting design conditions
  - System balancing using dampers only is not recommended
- Critical path
  - Design path of airflow (total flow resistance is maximum)
  - How to reduce the dynamic losses?

Air Duct Design & Sizing

- Reduce dynamic losses of the critical path
  - Maintain optimum air velocity through duct fittings
  - Emphasize reduction of dynamic losses nearer to the fan outlet or inlet (high air velocity)
  - Proper use of splitter vanes
  - Set 2 duct fittings as far apart as possible
- Air duct leakage
  - Duct leakage classification
    - ANSI, SMACNA, ASHRAE standards

Air Duct Design & Sizing

- Fire protection
  - Duct material selection
  - Vertical ducts (using masonry, concrete or clay)
  - When ducts pass through floors & walls
  - Use of fire dampers
  - Filling the gaps between ducts & bldg structure
  - Duct systems for industrial applications
- Any other fire precautions?

Why air duct has fire risk?

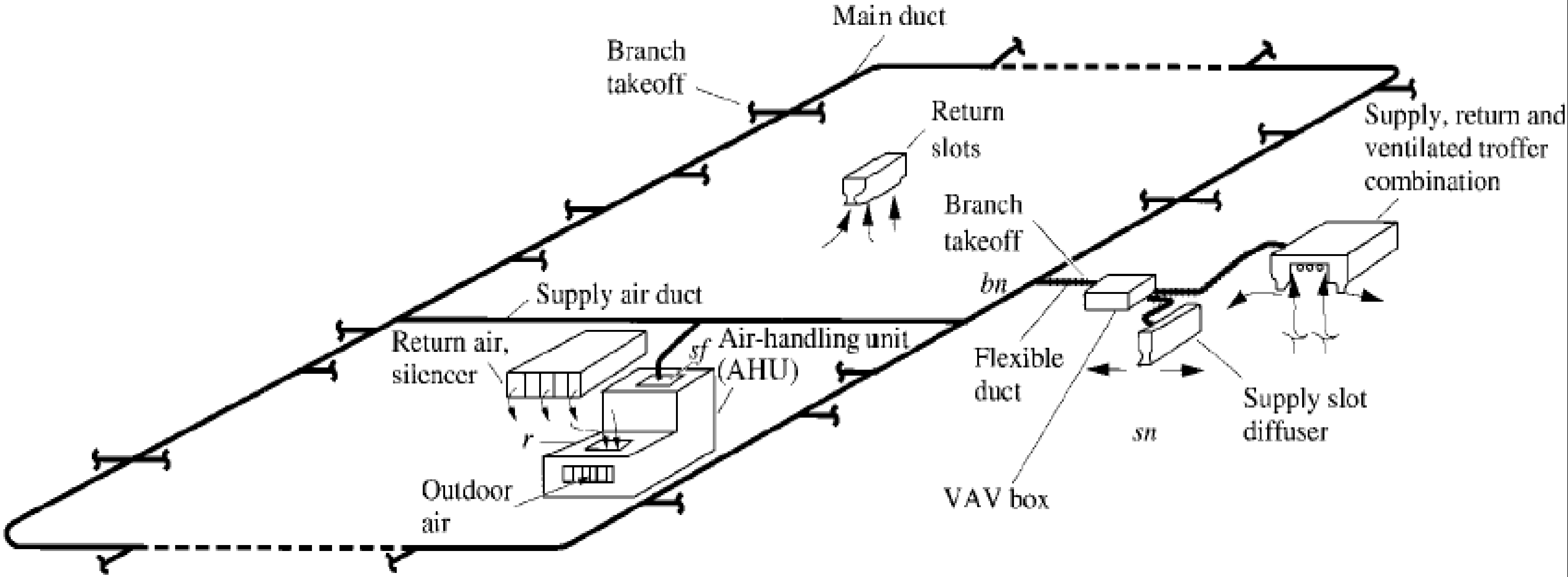
Air Duct Design & Sizing

- Design procedure (computer-aided or manual)
  - Verify local codes & material availability
  - Preliminary duct layout
  - Divide into consecutive duct sections
  - Minimise local loss coefficients of duct fittings
  - Select duct sizing methods
  - Critical total pressure loss of tentative critical path
  - Size branch ducts & balance total pressure at junctions
  - Adjust supply flow rates according to duct heat gain
  - Resize duct sections, recalculate & balance parallel paths
  - Check sound level & add necessary attenuation

Air Duct Design & Sizing

- Duct layout
  - Symmetric layout is easier to balance
    - Smaller main duct & shorter design path
  - For VAV systems, duct looping allows feed from opposite direction
    - Optimise transporting capacity (balance points often follow the sun's position)
    - Result in smaller main duct
  - Compare alternative layouts & reduce fittings
  - For exposed ducts, appearance & integration with the structure is important

Typical supply duct system with symmetric layout & looping



Do you know why symmetric layout & looping are used in this HVAC air duct system?

(Source: *Wang, S. K., 2001. Handbook of Air Conditioning and Refrigeration*)

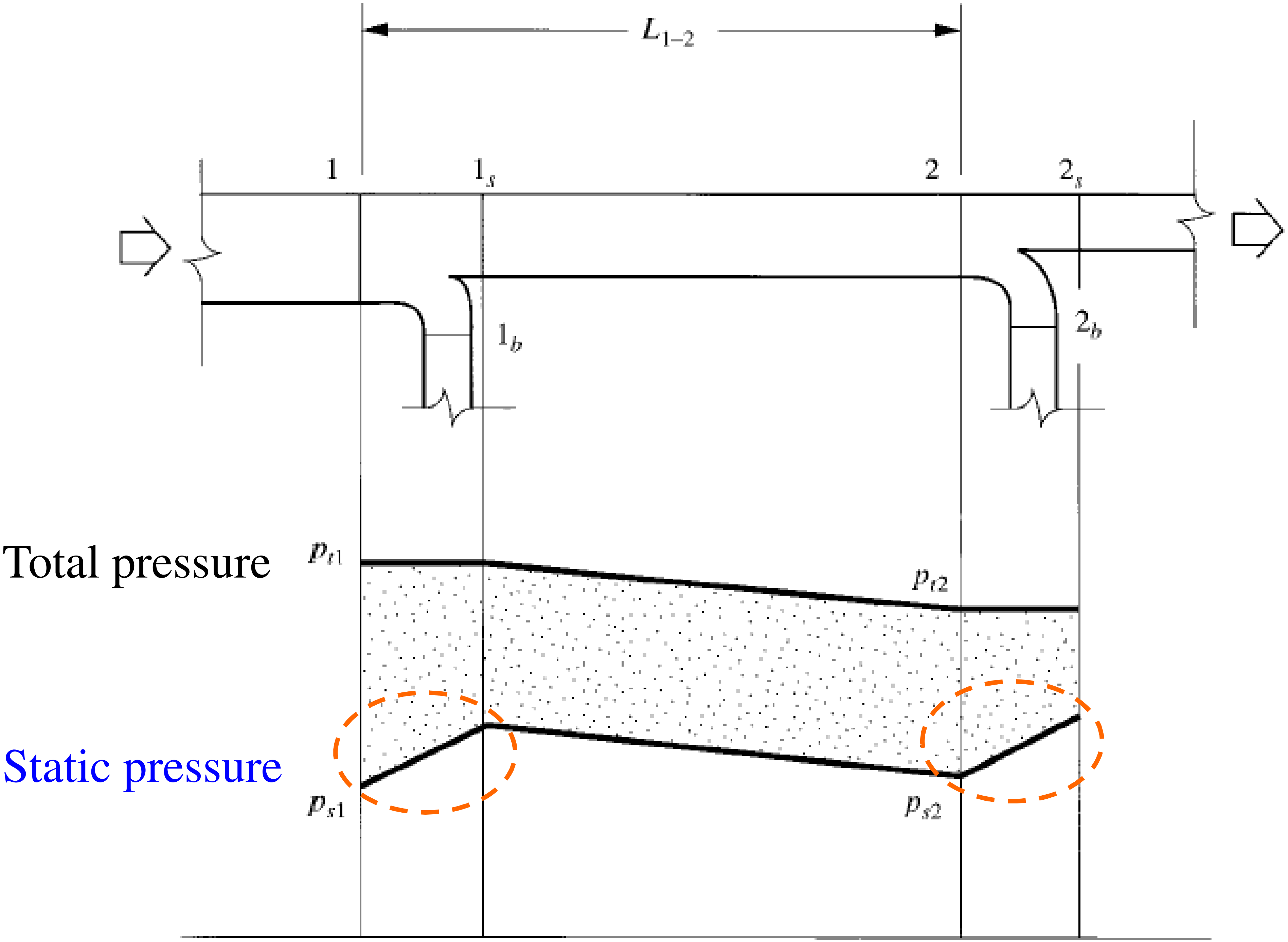
Air Duct Design & Sizing

- Duct sizing methods
  - Equal-friction method with maximum velocity
    - Duct friction loss per unit length remains constant
    - Most widely used in normal HVAC applications
  - Constant-velocity method
    - Often for exhaust ventilation system
    - Minimum velocity to carry dust is important
    - Limit velocity to reduce noise

Air Duct Design & Sizing

- Duct sizing methods
  - Static regain method
    - Normally used with a computer package for high velocity systems (e.g. in main duct)
    - Size air duct so that ↑static pressure nearly offset the pressure loss of succeeding duct section along main duct
  - T method
    - Optimising procedure by minimising life-cycle cost
      - System condensing (into a single imaginary duct)
      - Fan selection (optimum system pressure loss)
      - System expansion (back to original duct system)

Concept of static regain method



(Source: *Wang, S. K., 2001. Handbook of Air Conditioning and Refrigeration*)

Space Air Diffusion

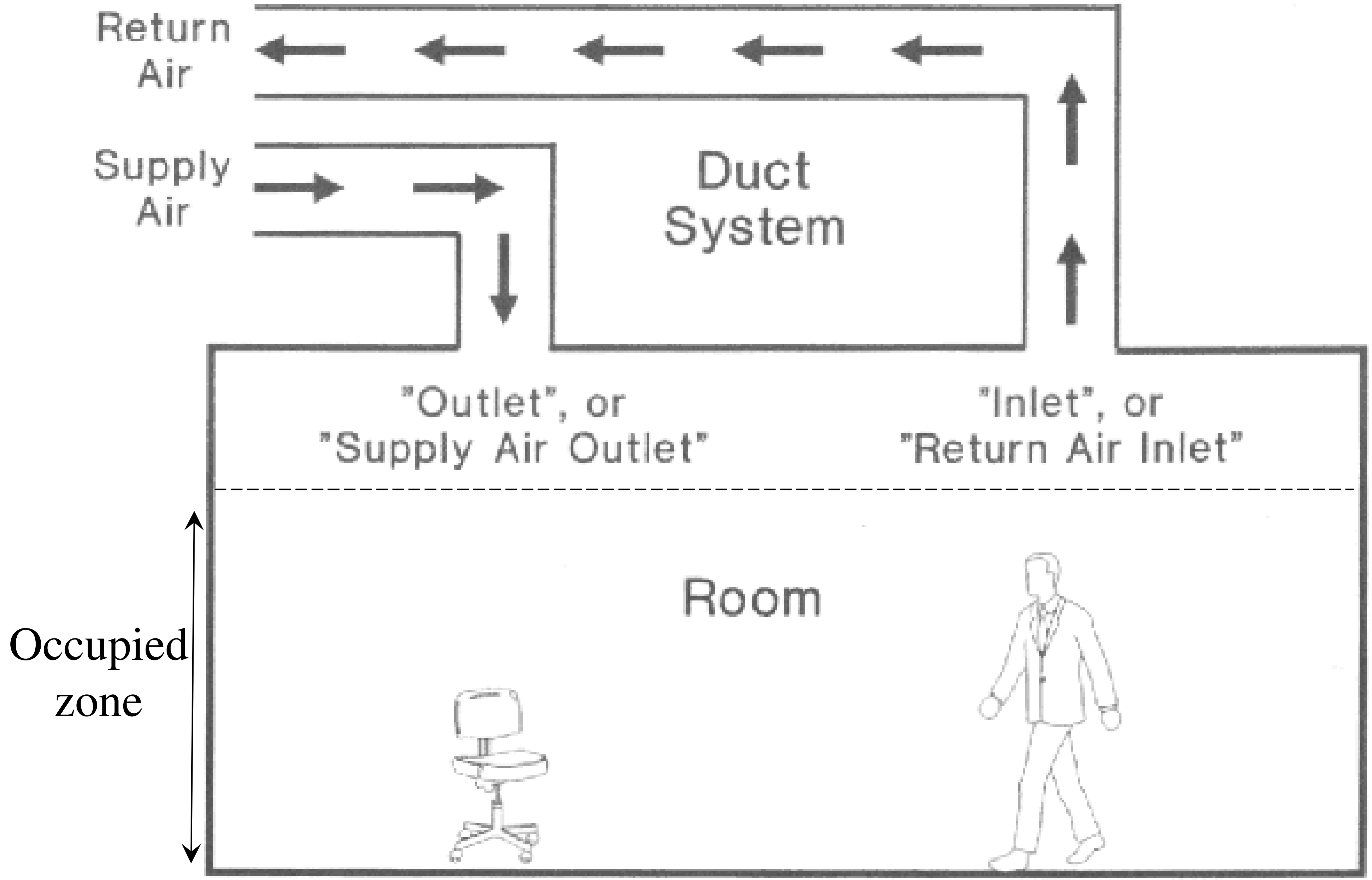
- Objective of space air diffusion
  - Evenly distribute conditioned & outdoor air to provide healthy & comfortable indoor environment, or appropriate environment for process, at optimum cost
- Last process of air conditioning
  - Take place entirely within conditioned space
  - Directly affect the occupants, but it is difficult to trace & quantify

Space Air Diffusion

- Important considerations:
  - Thermal comfort (temp., humidity, air velocity)
    - Comfort conditions, local variations
  - Indoor air quality
    - Airborne pollutants
    - Ventilation effects
  - Noise control
    - Noise criteria, sound attentuation
- Occupied zone: 1.8 m from floor

(Video: 3- Fundamentals of HVAC - Comfort Criteria (9:56) http://www.youtube.com/watch?v=qZ3RwH018Qw)

Air distribution in HVAC duct system and room



(Video: 4- Fundamentals of HVAC - Space Air Diffusion (8:37) http://www.youtube.com/watch?v=zephL3PidMI)

(Source: Rock, B. A. and Zhu, D., 2002. *Designer's Guide to Ceiling-based Air Diffusion*.)

Space Air Diffusion

Thermal Comfort

- Draft & effective draft temperature
  - Draft: unwanted local cooling of human body caused by air movement & lower space air temp.
  - Turbulence intensity, $I_{tur} = \sigma_v / v_m$
    - σ_v = standard deviation of air velocity fluctuation (m/s)
    - v_m = mean air velocity (m/s)
  - Effective draft temperature: combines effects of uneven space air temp. & air movement
    - $\theta = T_x - T_r - a\,(v_x - v_{rm})$

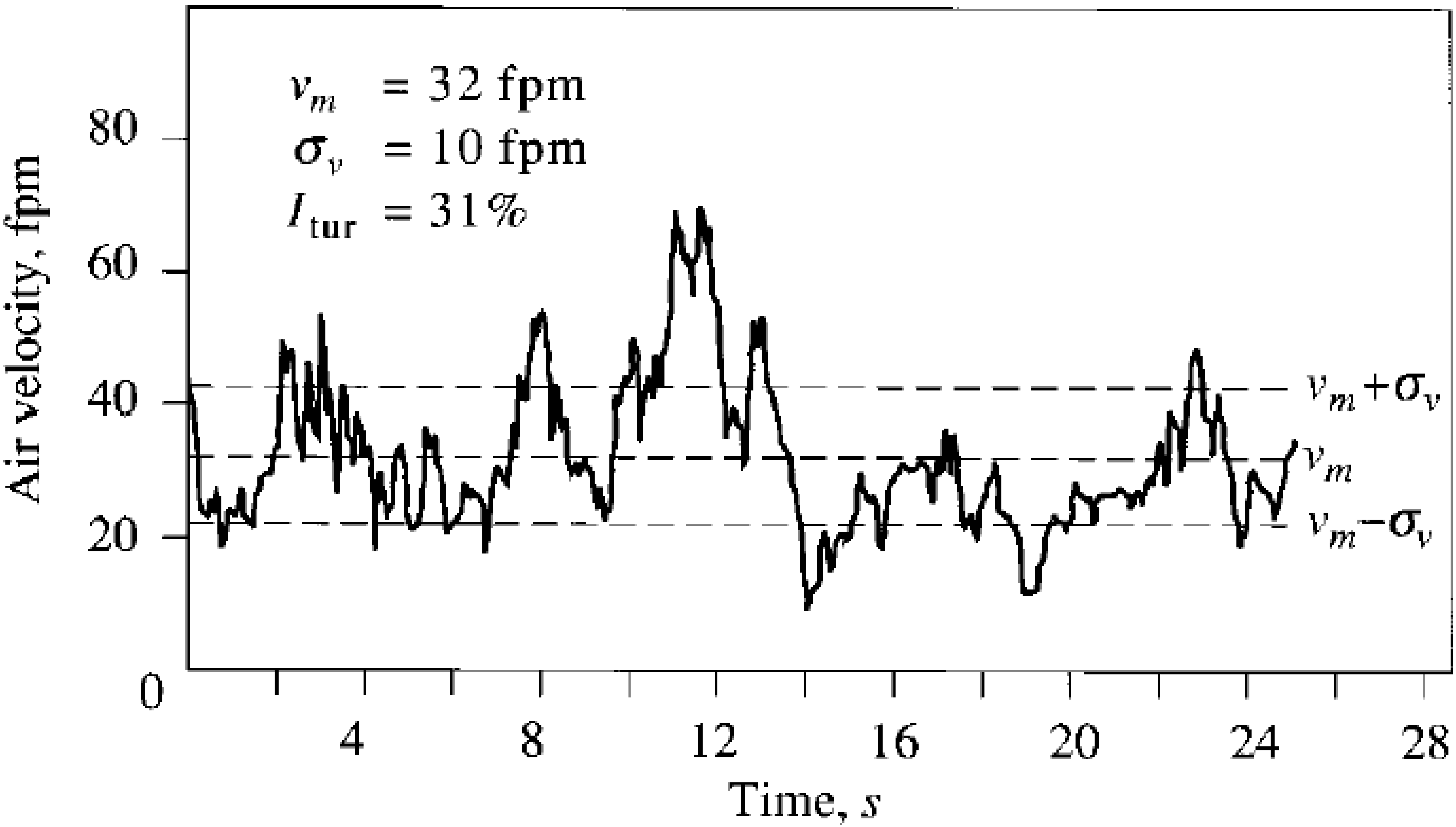


FIGURE 18.1 Fluctuations of air velocity in a typical air conditioned space. (*Adapted with permission from ASHRAE Journal, April 1989, p. 30.*)

(Source: *Wang, S. K., 2001. Handbook of Air Conditioning and Refrigeration*)

Space Air Diffusion

- Air diffusion performance index (ADPI)
  - ADPI = (N_θ x 100) / N
    - θ: effective draft temperature
    - N_θ: number of points measured in occupied zone in which $-1.7\ ^oC < \theta < 1.1\ ^oC$
    - N : total number of points measured in occupied zone
  - Higher the ADPI, higher % of occupants who feel comfortable
  - ADPI is useful for cooling mode operation
  - For heating mode, temperature gradient ⁒ 2 points may be a better indicator of thermal comfort ($< 2.8\ ^oC$ typical)

Space Air Diffusion

- Air exchange rate
  - = Volume flow rate / interior volume
  - Unit: L/s or air change per hour (ACH)
  - May consider outside air, or supply air
- Time constant (τ)
  - Inverse of air exchange rate
- Air diffusion effectiveness
  - Perfectly mixing, perfectly displacing
  - Degree of effectiveness of air diffusion

Space Air Diffusion

- Space diffusion effectiveness factor
  - For air temperature or air contamination

$$\varepsilon_T = \frac{T_{re} - T_s}{T_r - T_s} = \frac{T_{ex} - T_s}{T_r - T_s}$$

$$\varepsilon_C = \frac{C_{ex} - C_s}{C_r - C_s}$$

  - Subscript: re = recirculating air; ex = exhaust air; r = space air; s = supply air
  - Effective if ε= 1; not so if ε< 1

Space Air Diffusion

- Ventilation effectiveness
  - Air system's ability to remove internally generated contaminants from a zone, space or building
- Age of air θ_{age} (in minutes or hours)
  - Time period that outdoor ventilation air has been in a zone, space or building
  - Evaluated using tracer gas method
  - The "youngest" air = freshest air

Space Air Diffusion

- Air change effectiveness ε_N
  - Air system's ability to deliver ventilation air
    - How well outdoor air is diffused to various locations
  - $\varepsilon_N = \tau_N / \theta_{age,\,N}$
    - τ_N : nominal time constant (min. or hr.)
      - ACH = supply volume flow rate / space volume
      - $\tau_N = 1$ / ACH
  - For proper air distribution system, $\varepsilon_N \approx 1$

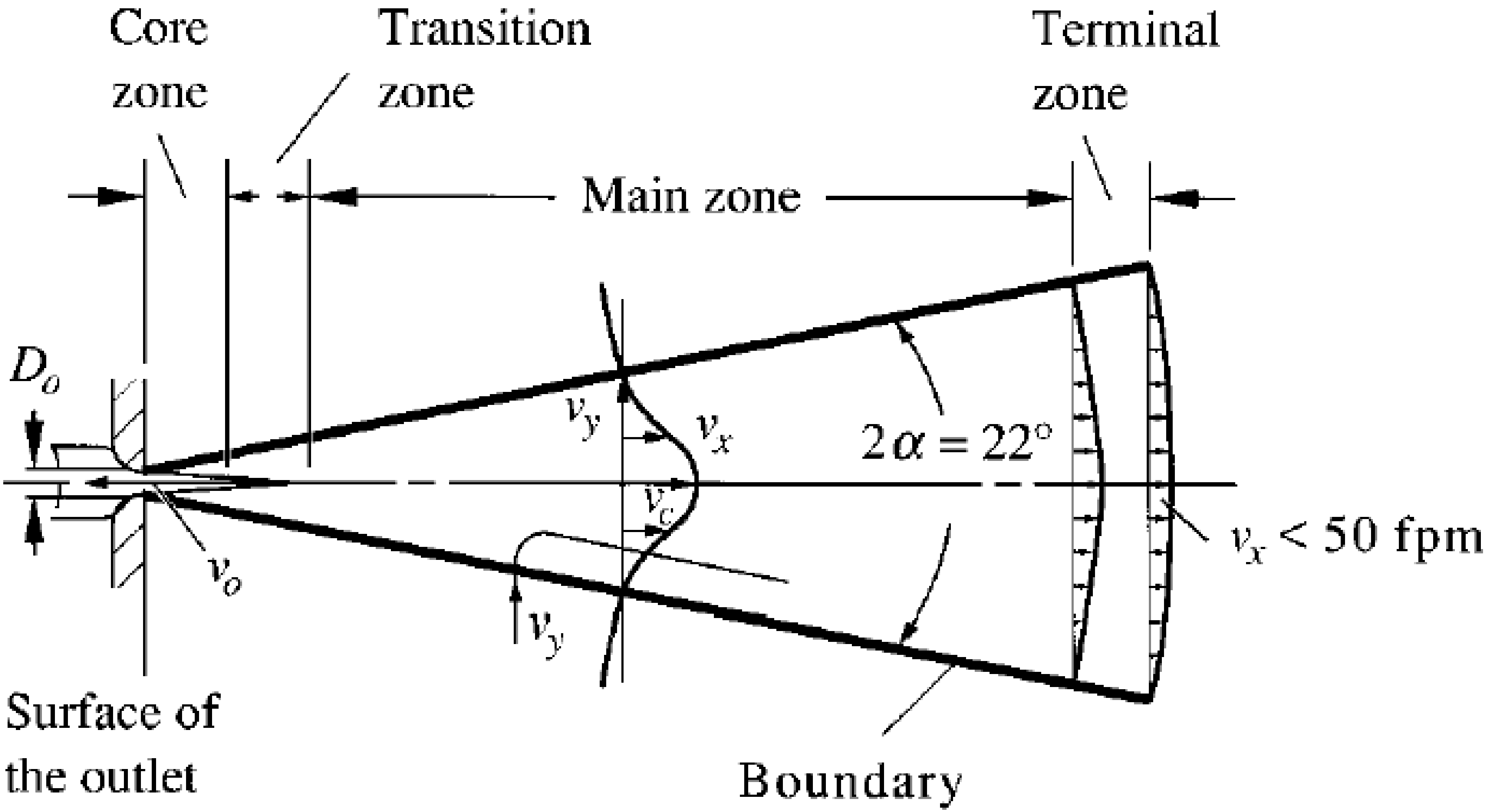
Air Jets

- Air jets
  - Airstream discharge from an outlet with significantly higher velocity than surrounding
    - Move along its centreline until terminal velocity reduces to velocity of ambient air
  - Envelope = outer boundary of air jet
  - Common classifications
    - Free or confined
    - Isothermal or non-isothermal
    - Axial or radial

Air Jets

- Air jets
  - Free air jet: envelope not confined by enclosure
  - Confined air jet: envelope confined by ceiling, floor, walls, windows, furniture, etc
    - Air jet approaches a free air jet if $\sqrt{A_r} / D_o > 50$
      - A_r = cross-sectional area of the enclosure perpendicular to the air jet centreline
      - D_o = diameter or circular equivalent of supply outlet
  - Isothermal jets: whose temperature is equal to the ambient air (c.f.: non-isothermal jets)

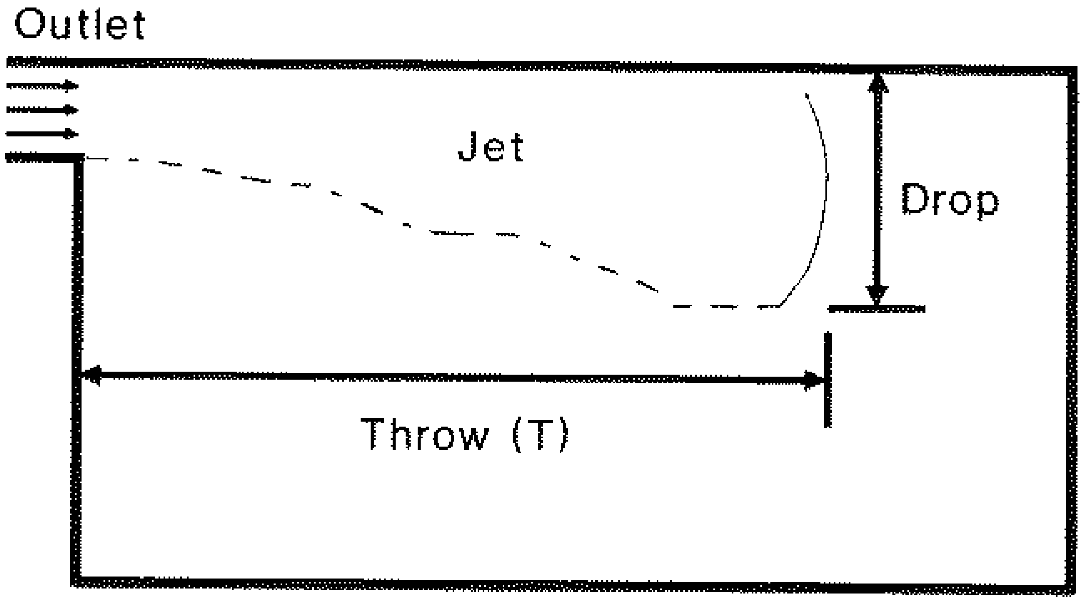
Four zones of a free, isothermal, axial air jet



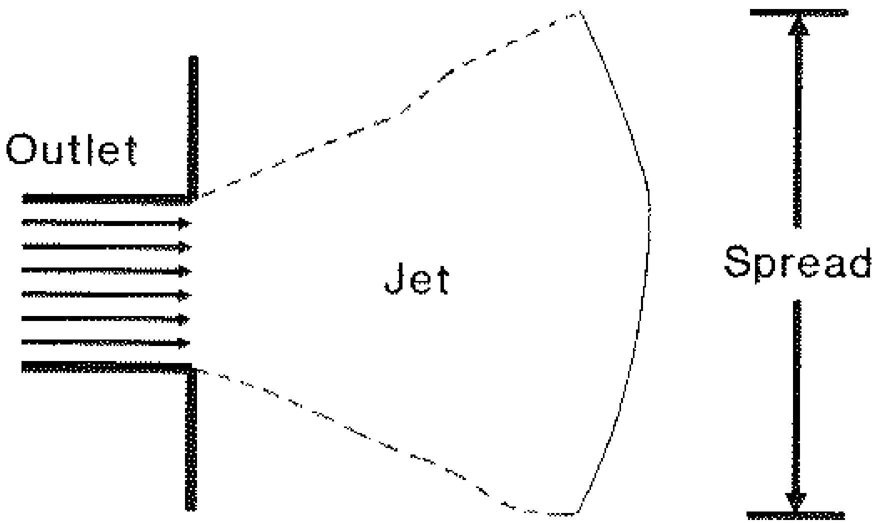
(Source: *Wang, S. K., 2001. Handbook of Air Conditioning and Refrigeration*)

Air Jets

- Free isothermal jets
  - Core zone
    - Centreline velocity remains unchanged
    - Extends about 4 D_o from the outlet
  - Transition zone
    - Centreline velocity decreases inversely w/ square root of distance from outlet
    - Extends about 8 D_o from the outlet
  - Main zone
    - Turbulent flow is fully developed
    - Extends about 25-100 D_o from the outlet
  - Terminal zone
    - Max. air velocity decreases rapidly to less than 0.25 m/s



Section View



Plan View

(Source: Rock, B. A. and Zhu, D., 2002. *Designer's Guide to Ceiling-based Air Diffusion*.)

Air Jets

- Throw, T_v (m)
  - Horizontal or vertical axial distance from outlet to a cross-sectional plane where max. velocity of airstream at the terminal zone has been reduced to 0.25, 0.5, or 0.75 m/s

$$T_v = \frac{K' \times \dot{V}_s}{v_{t,\max}\sqrt{A_c C_d R_{fa}}}$$

K' = centreline velocity constant
V_s = supply volume flow rate
$v_{t,\max}$ = max. velocity at terminal zone
A_c = core area of outlet
C_d = discharge coefficient
R_{fa} = ratio of free area to gross area

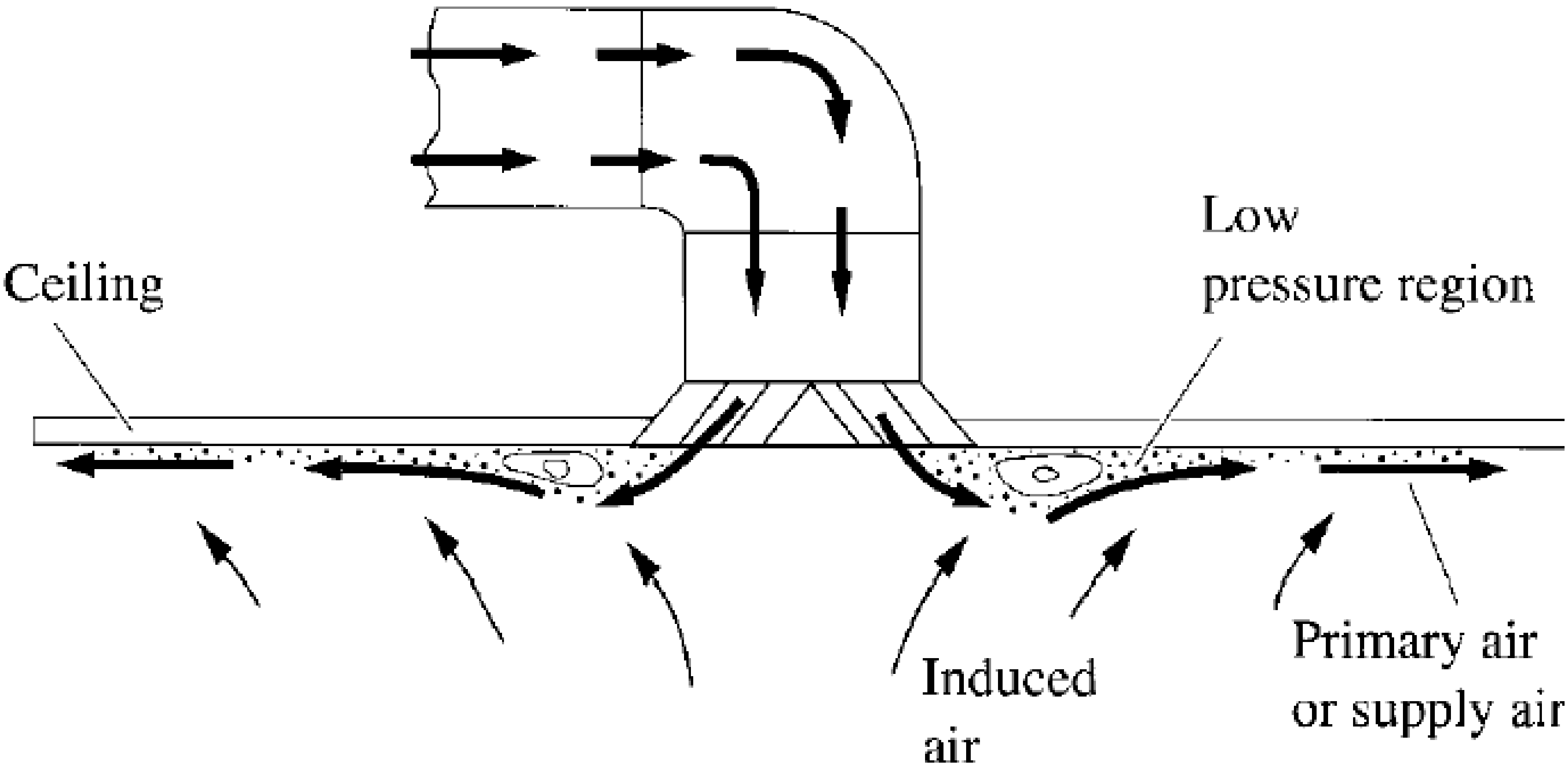
Air Jets

- Entrainment ratio
  - Ratio of volume flow rate to the total air at a specific cross-sectional plane of the air jet to volume flow rate of the supply air discharged from outlet (primary air)
  - Total air = sum of supply air and induced air
  - Proportional to the distance or square root of the distance from outlet

Air Jets

- Confined air jets (in practical cases)
  - Surface effect (or Coandă effect)
    - Primary airstream from supply outlet flows along a surface (at high velocity)
    - A lower pressure region is formed near the surface
    - Induced ambient air presses the air jet to the surface
    - Friction between airstream & boundary
      - Decreases the centreline velocity of the air jets
    - With the surface effect, throw of a confined air jet is longer, drop from horizontal axis smaller than that of a free air jet

Surface effect (or Coandă effect)



(Source: *Wang, S. K., 2001. Handbook of Air Conditioning and Refrigeration*)

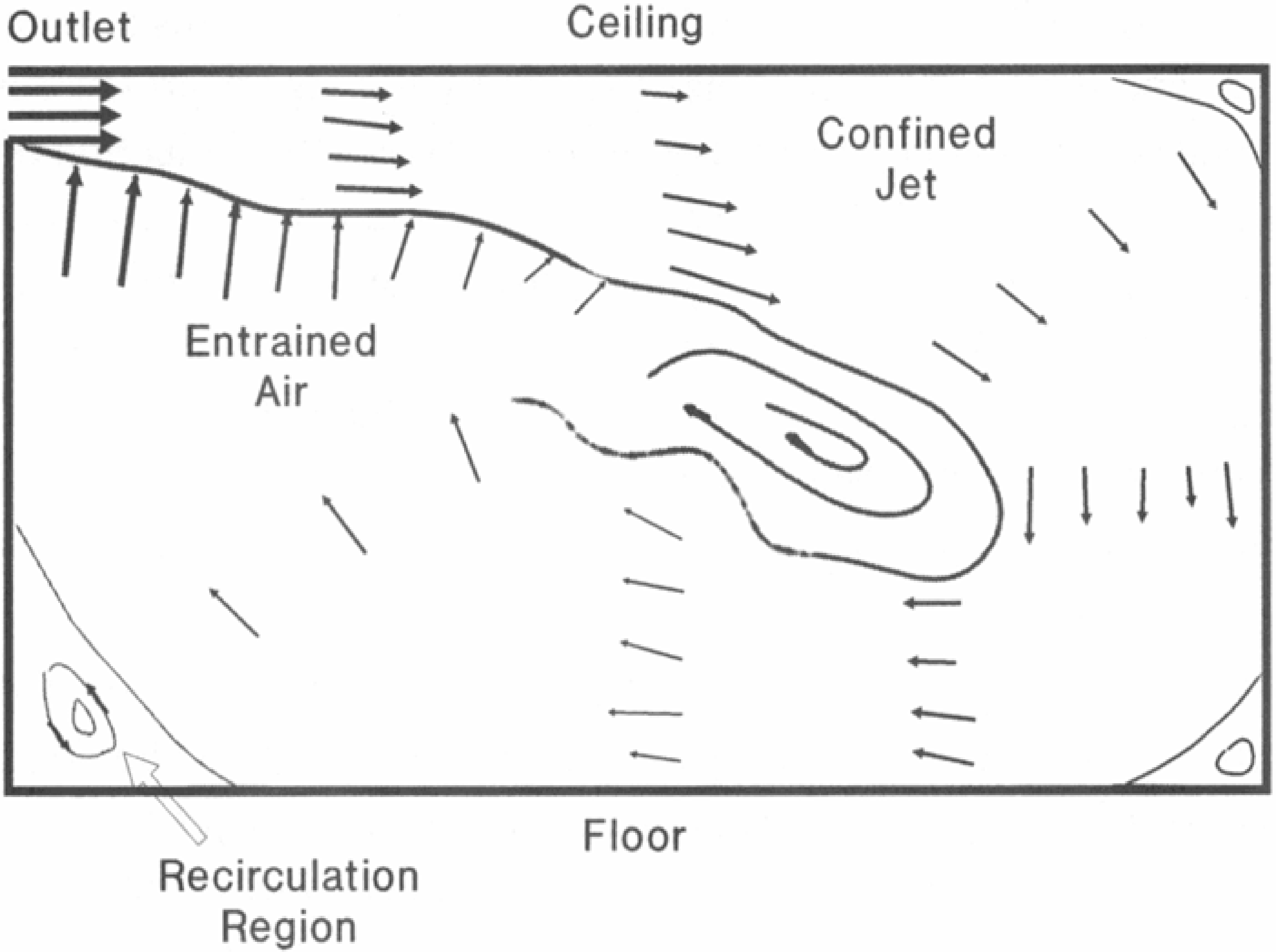
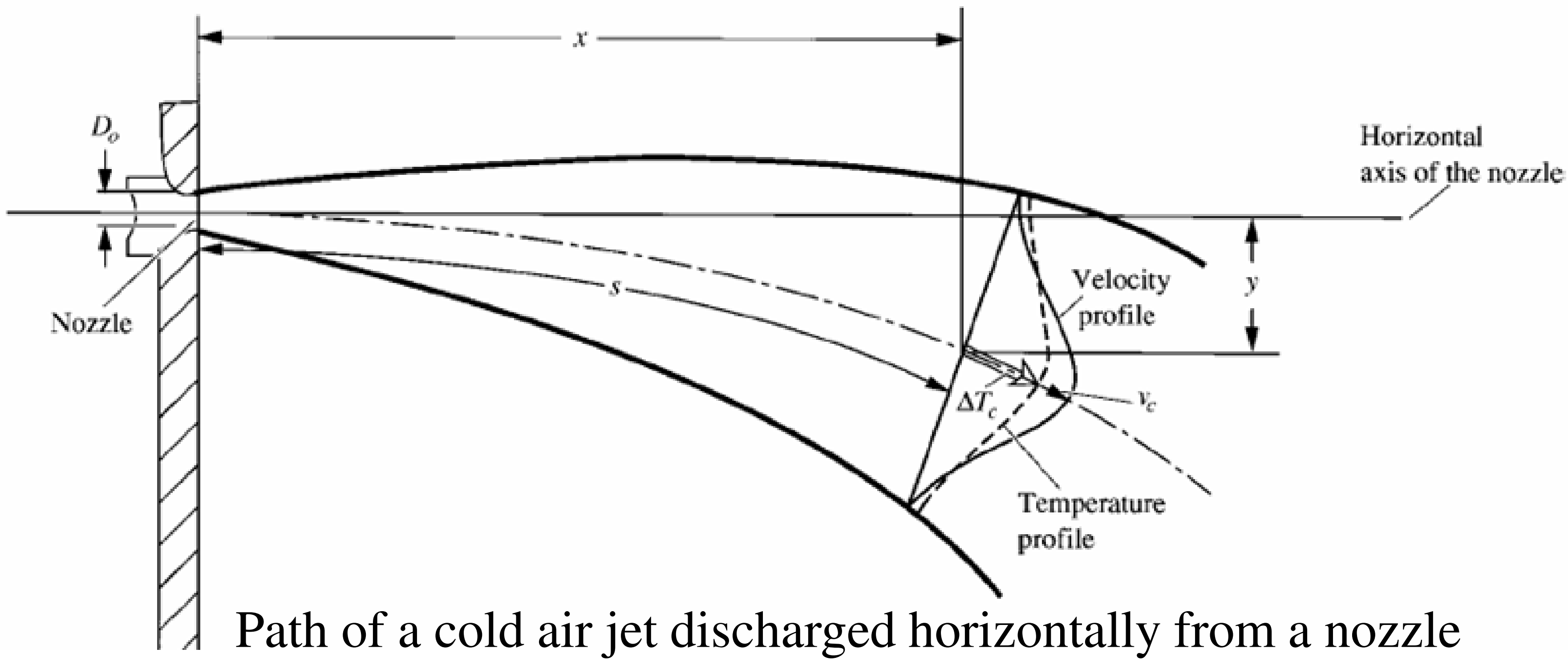


Figure 5.11 *Because a real room has a limited volume, a jet's growth and shape are affected. A "confined jet" is the result.*

(Source: Rock, B. A. and Zhu, D., 2002. *Designer's Guide to Ceiling-based Air Diffusion*.)

Air Jets

- Free nonisothermal jets
  - Supply air at different temp. from ambient air
  - Buoyancy of air causes trajectory of the air jet



Path of a cold air jet discharged horizontally from a nozzle

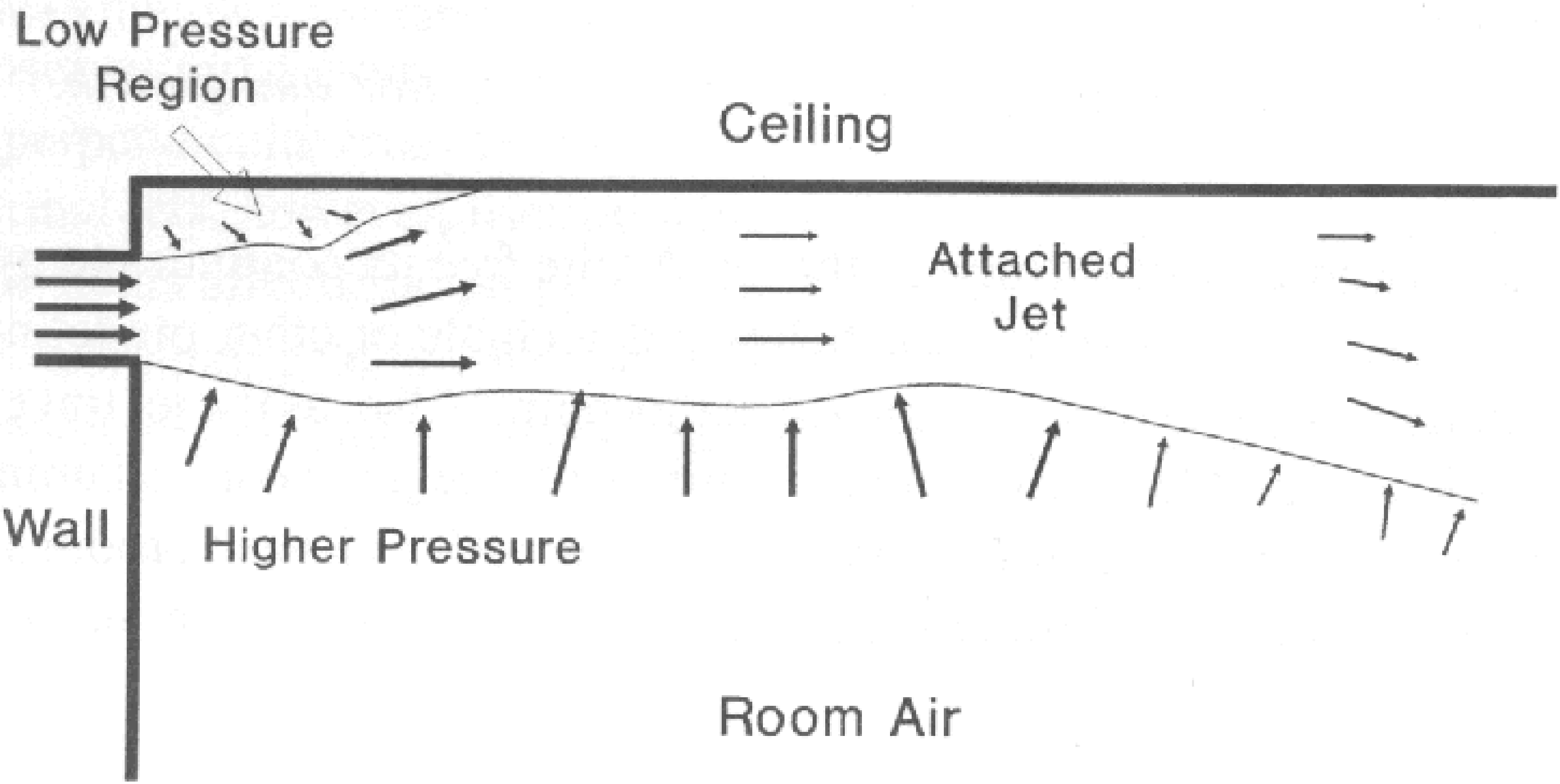


Figure 5.9 *A jet attaches to a surface like a ceiling because entrainment is limited on that side.*

(Source: Rock, B. A. and Zhu, D., 2002. *Designer's Guide to Ceiling-based Air Diffusion*.)

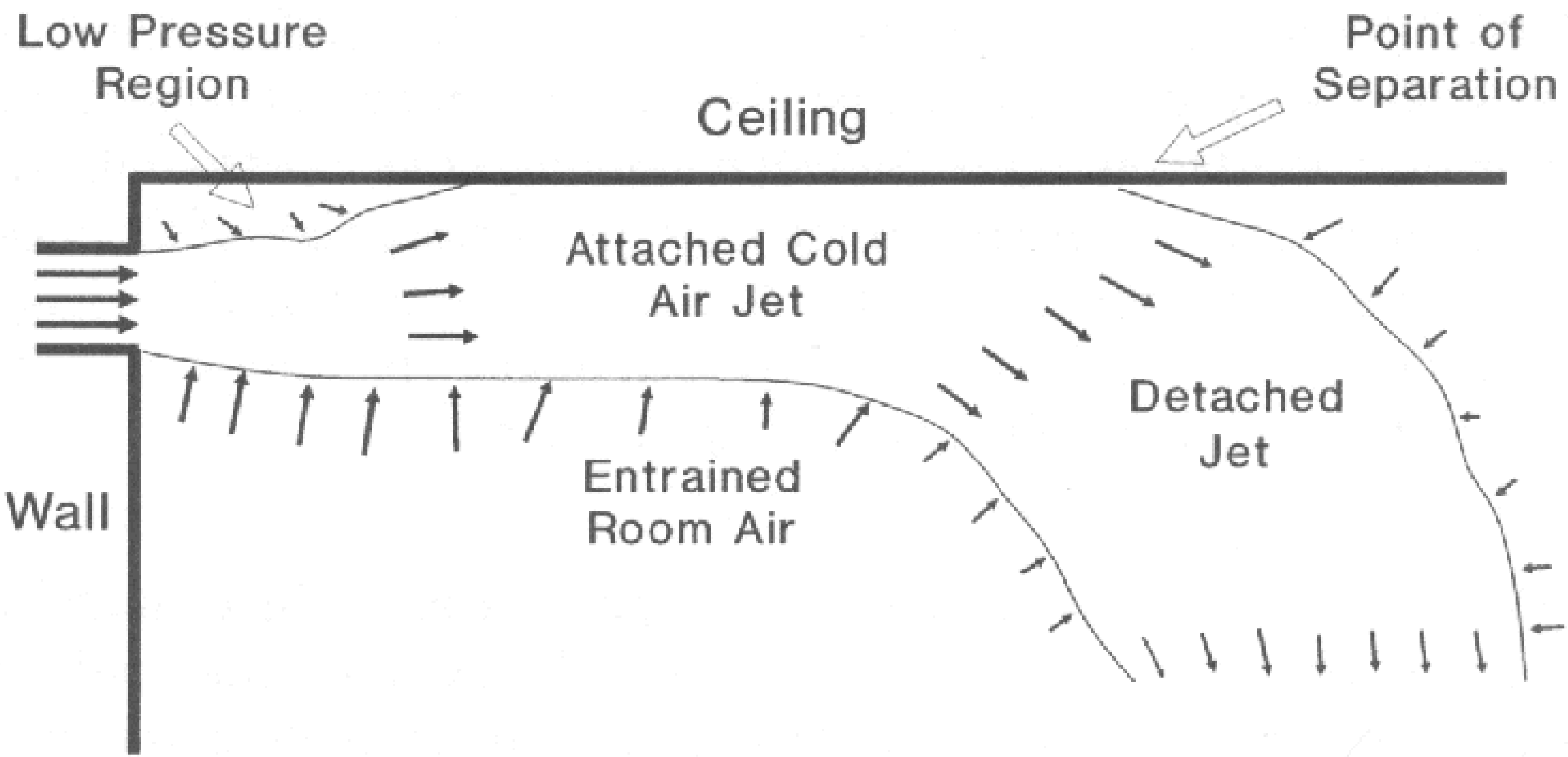


Figure 5.10 *If a cool air ceiling jet slows to the point that negative buoyancy overcomes the force causing attachment, the jet detaches from the ceiling.*

(Source: Rock, B. A. and Zhu, D., 2002. *Designer's Guide to Ceiling-based Air Diffusion*.)

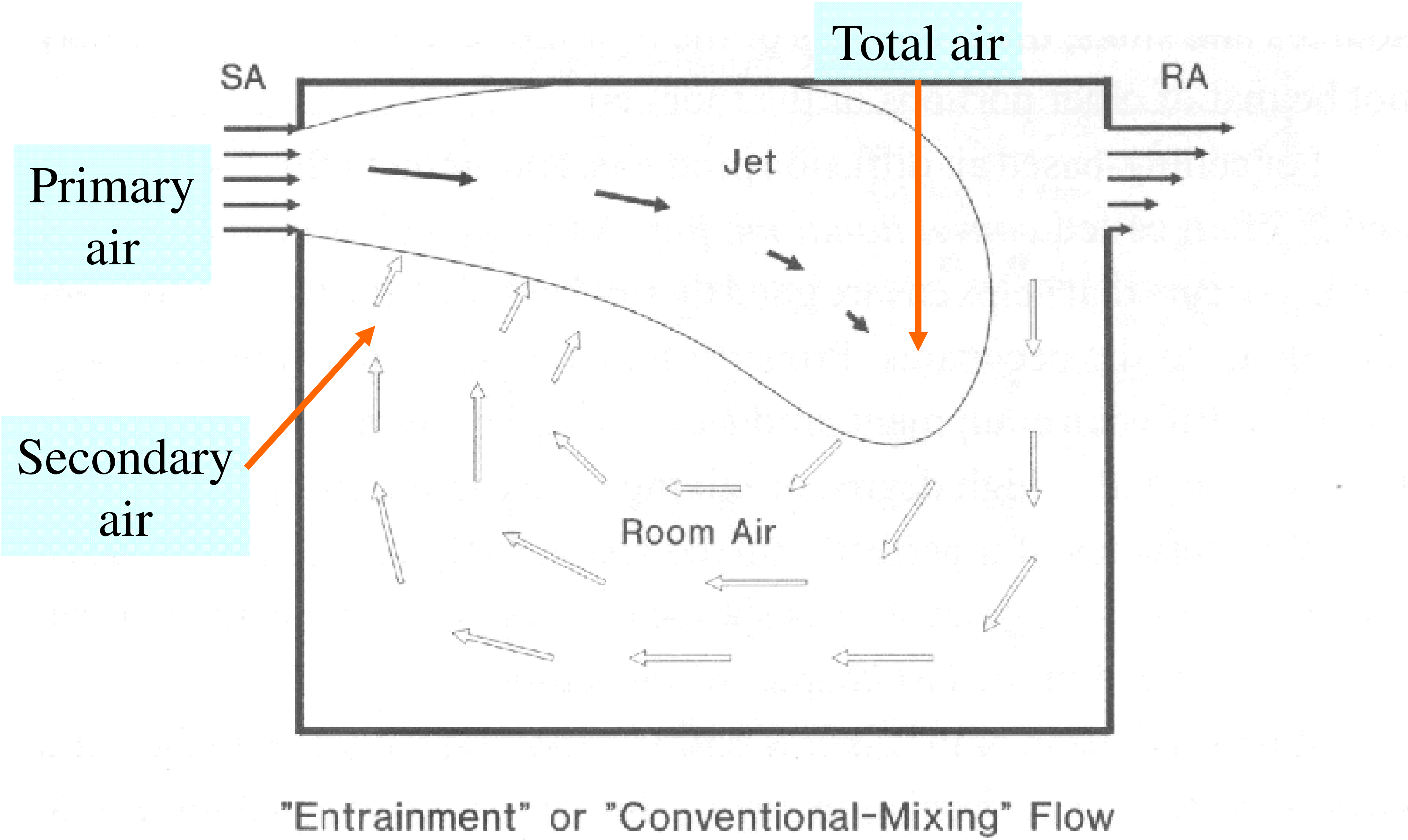


Figure 6.2 *Real airflows in rooms are most often "entrainment flow" or "conventional mixing" where confined jets and surfaces affect the resulting pattern.*

(Source: Rock, B. A. and Zhu, D., 2002. *Designer's Guide to Ceiling-based Air Diffusion.*)

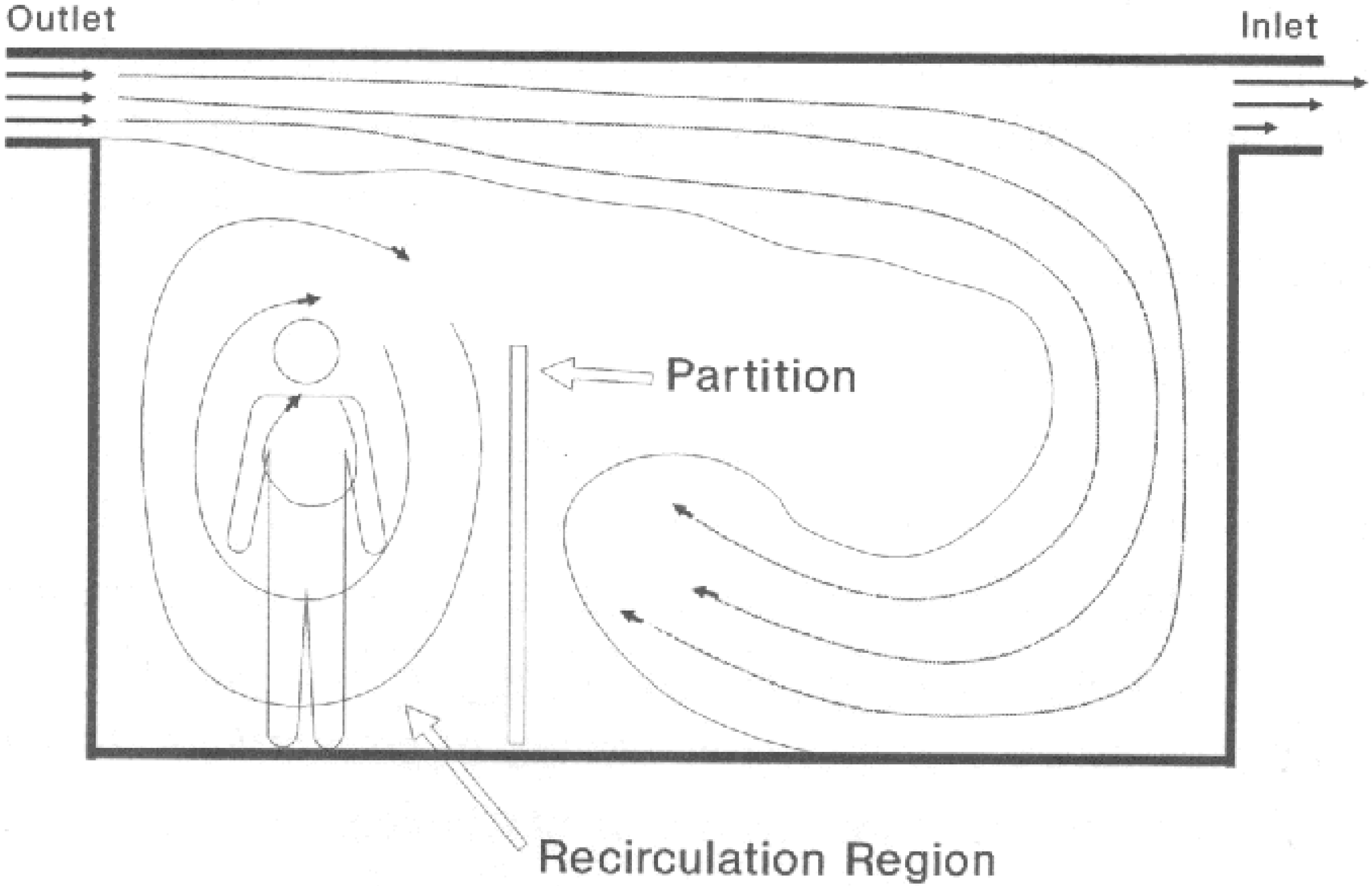


Figure 6.3 *Recirculation regions often form due to limiting objects and surfaces within spaces, or the characteristics of the jet and the room.*

(Source: Rock, B. A. and Zhu, D., 2002. *Designer's Guide to Ceiling-based Air Diffusion*.)

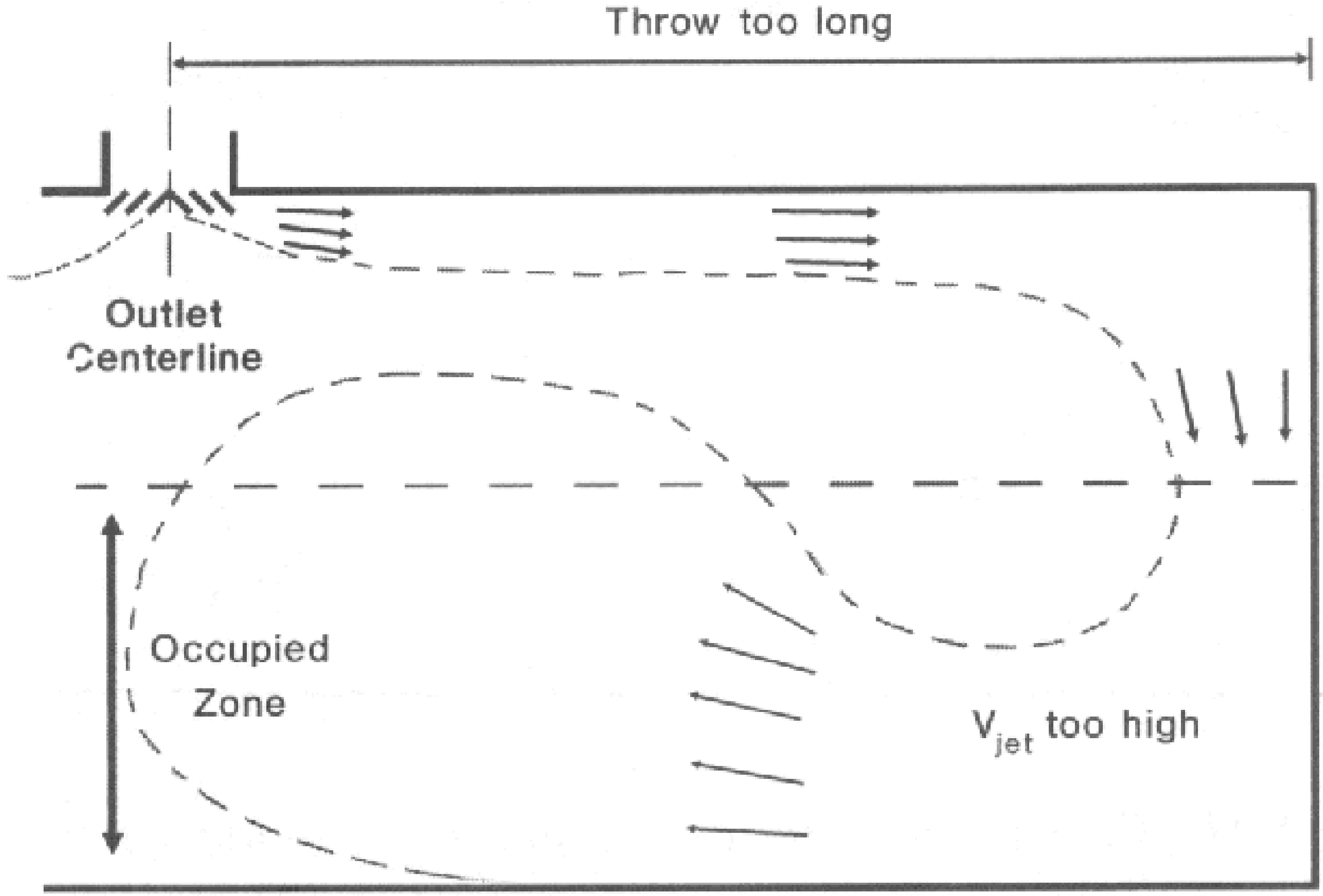


Figure 6.9 *When a jet's throw is too long, the velocity and the temperature of the air entering the occupied zone may be objectionable.*

(Source: Rock, B. A. and Zhu, D., 2002. *Designer's Guide to Ceiling-based Air Diffusion*.)

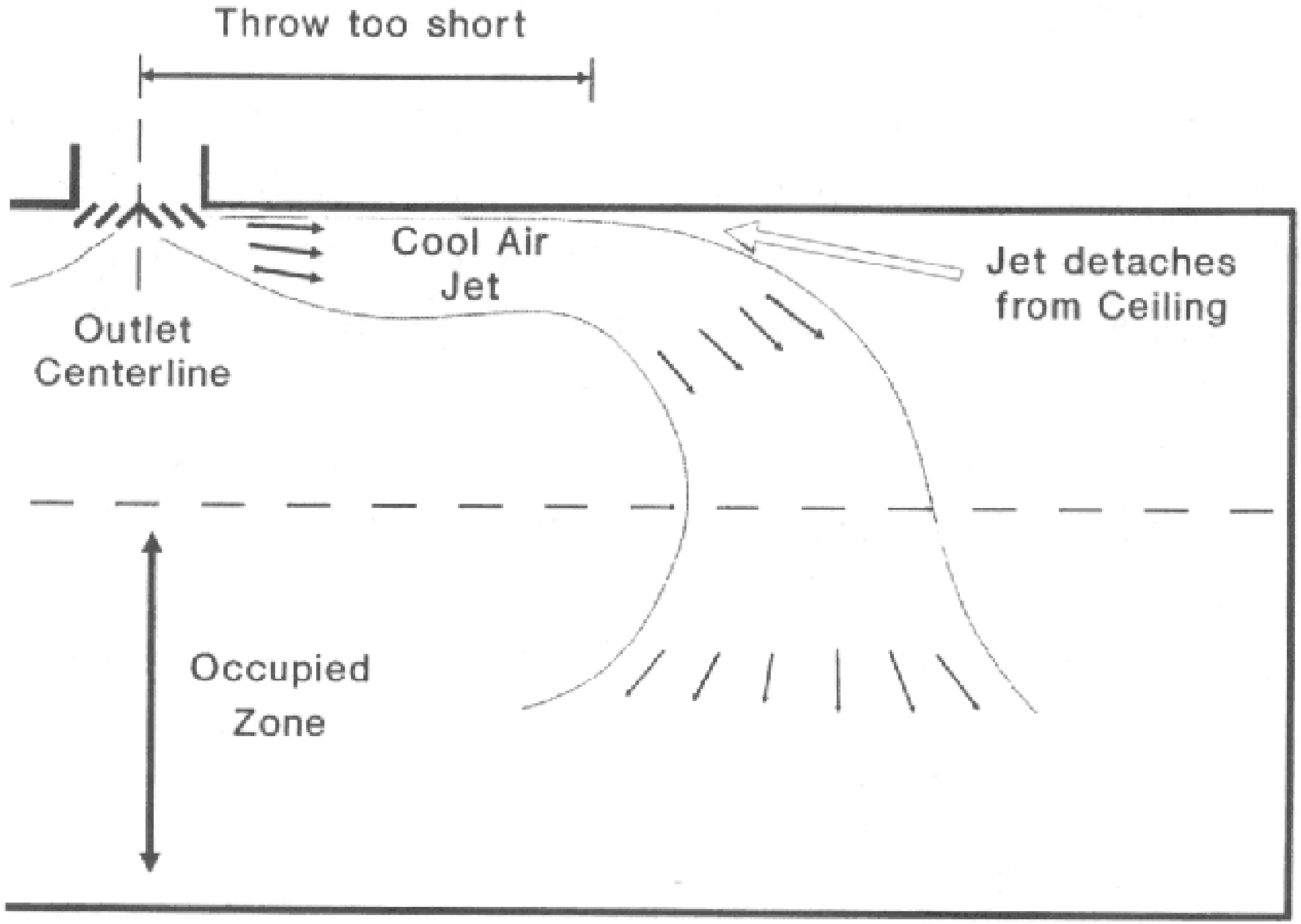


Figure 6.10 *"Dumping" is when a jet enters the occupied zone and is objectionable. Detachment is one potential cause of dumping, and can be created by too little airflow and/or an oversized outlet.*

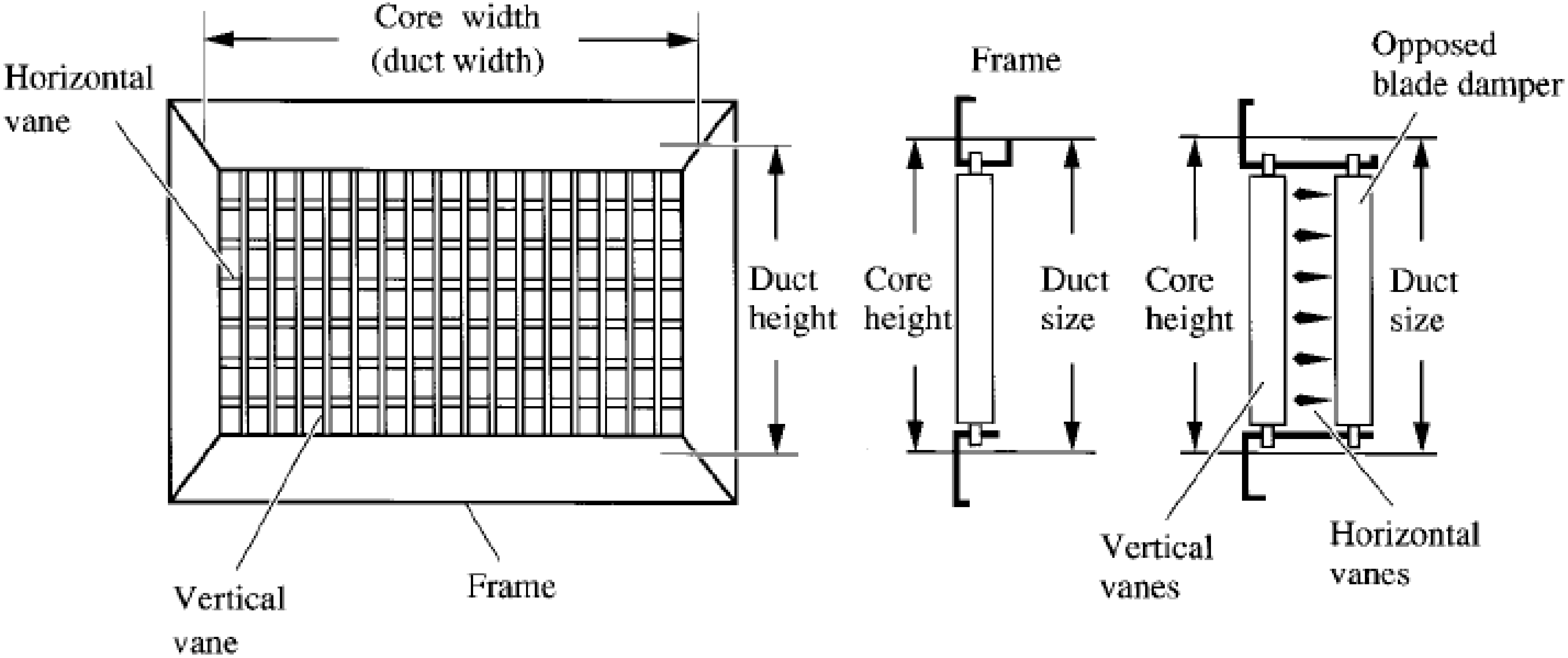
(Source: Rock, B. A. and Zhu, D., 2002. *Designer's Guide to Ceiling-based Air Diffusion*.)

Outlets and Inlets

- Supply outlets
  - Grilles and registers
  - Ceiling diffusers
  - Slot diffusers
  - Nozzles
- Return & exhaust inlets
- Light troffer diffuser & troffer-diffuser slot
- Design issues: architectural setup, airflow pattern needed, indoor requirements, load conditions

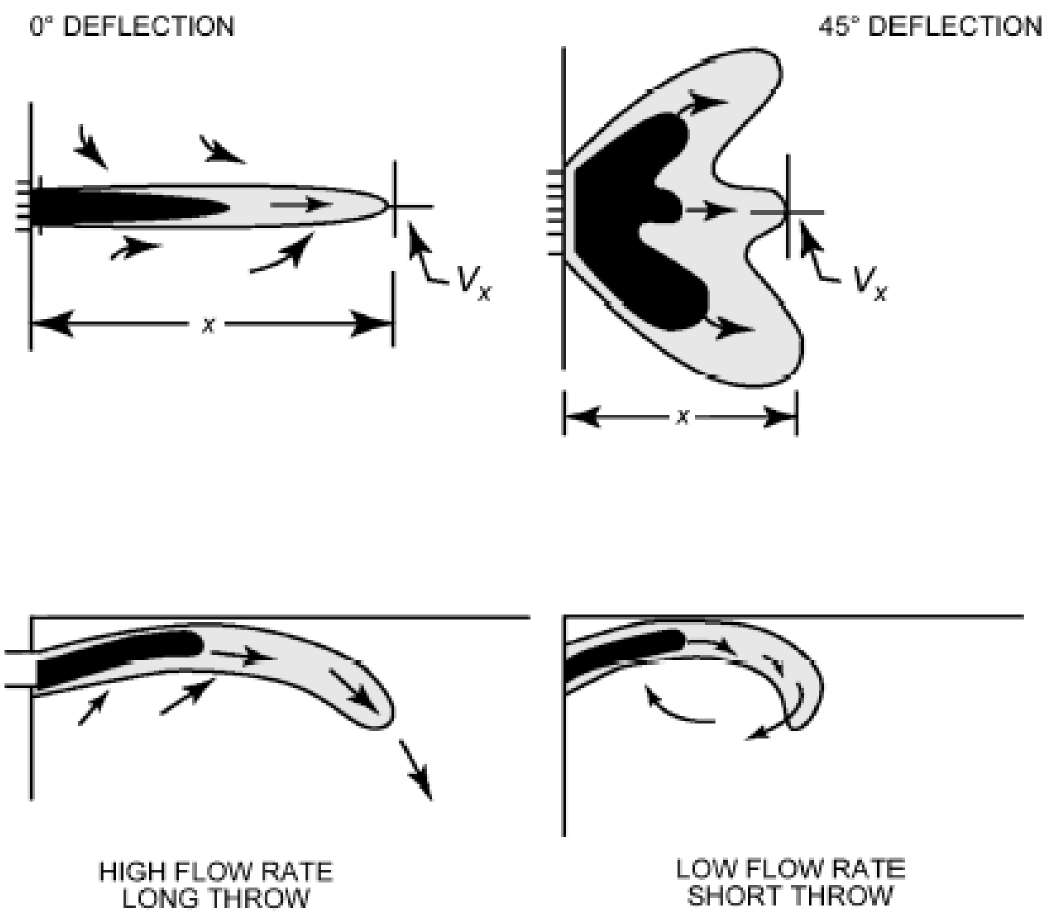
(Video: 7- Fundamentals of HVAC - Air Outlet Selection (32:28) http://www.youtube.com/watch?v=OvVCCljuluY)

Supply grille and register

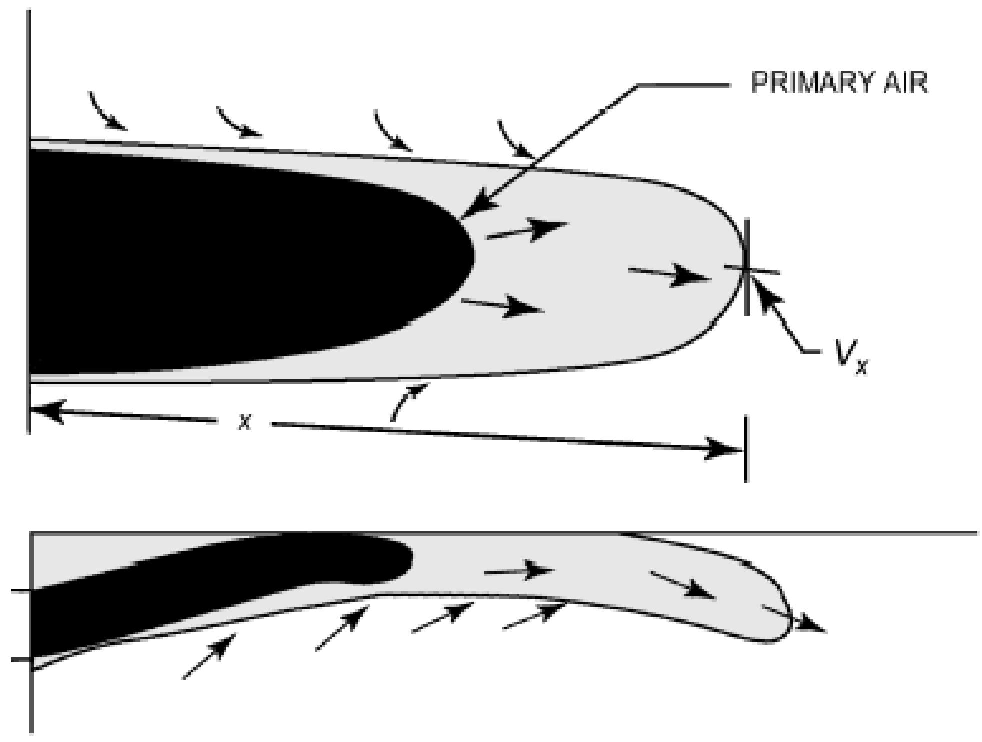


(Source: *Wang, S. K., 2001. Handbook of Air Conditioning and Refrigeration*)

Airflow patterns of high sidewall supply grilles



A. HIGH SIDEWALL GRILLES



Note: Throw values based on 1.2 m long, isothermal active section.
Correction multipliers for other lengths are as follows:

Active length, m	0.6	1.2	2.4	3
Throw correction	0.72	1	1.5	1.7

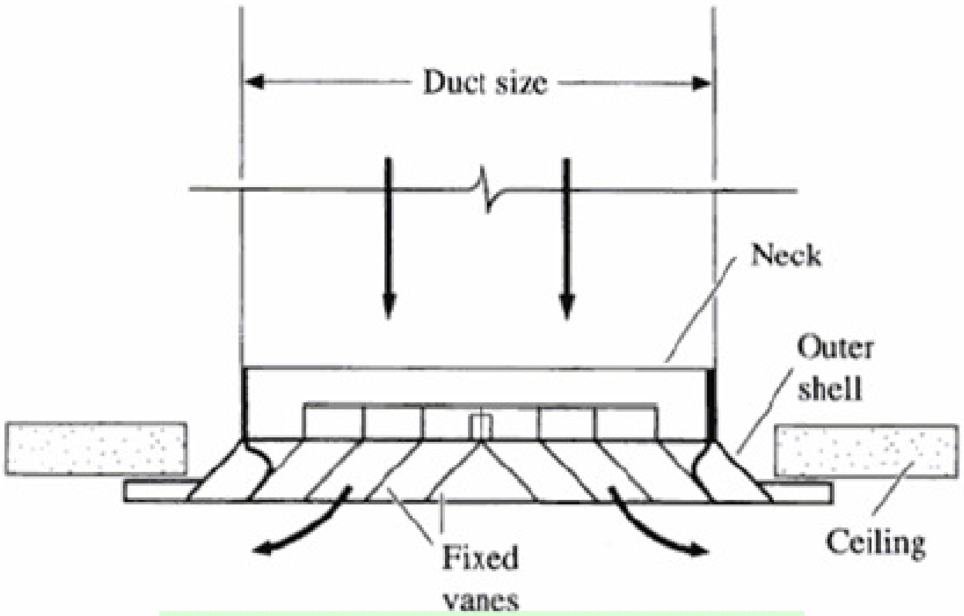
B. HIGH SIDEWALL LINEAR

(Source: *ASHRAE Handbook Fundamentals 2001*)

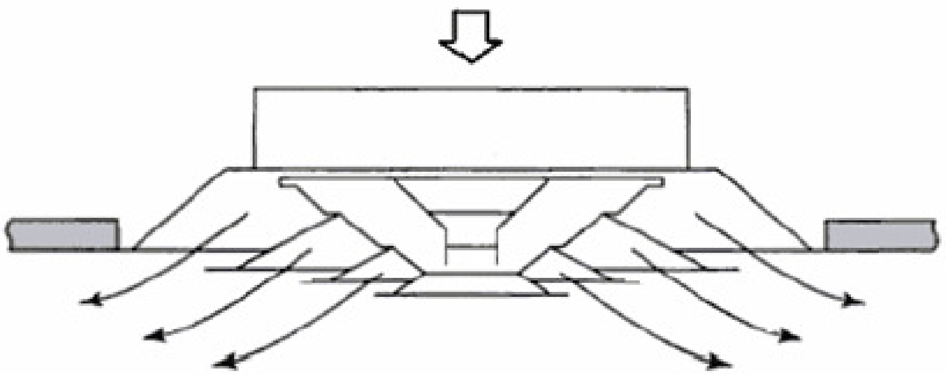
Outlets and Inlets

- Performance data of grilles and registers
  - Core size or core area
  - Volume flow rate
  - Air velocity
  - Total pressure loss
  - Throw at various terminal velocities
  - Noise criteria curve

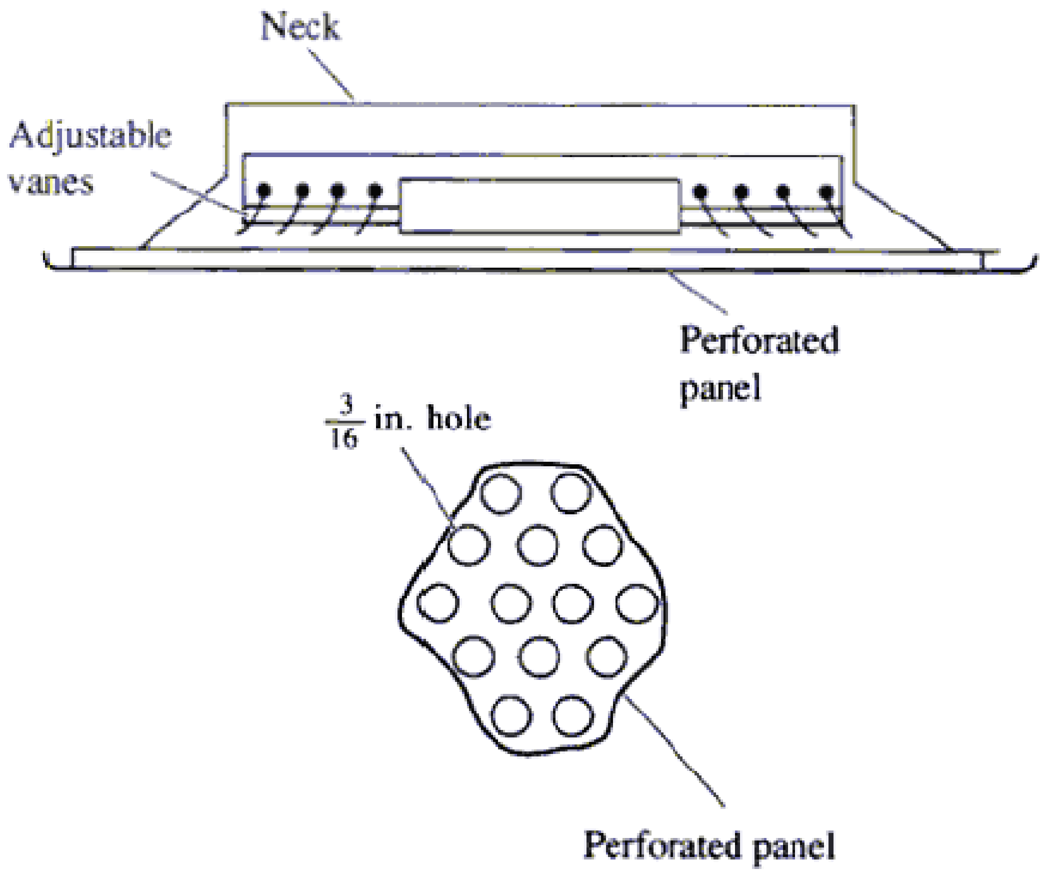
Ceiling diffusers



Square & rectangular



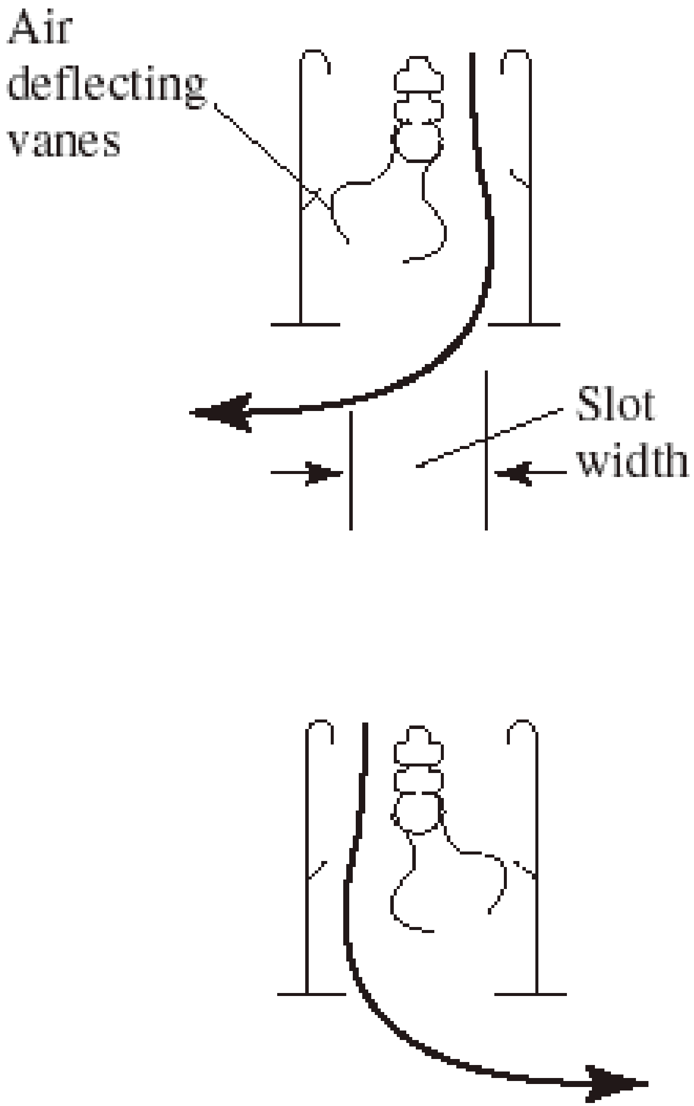
Removable inner-core

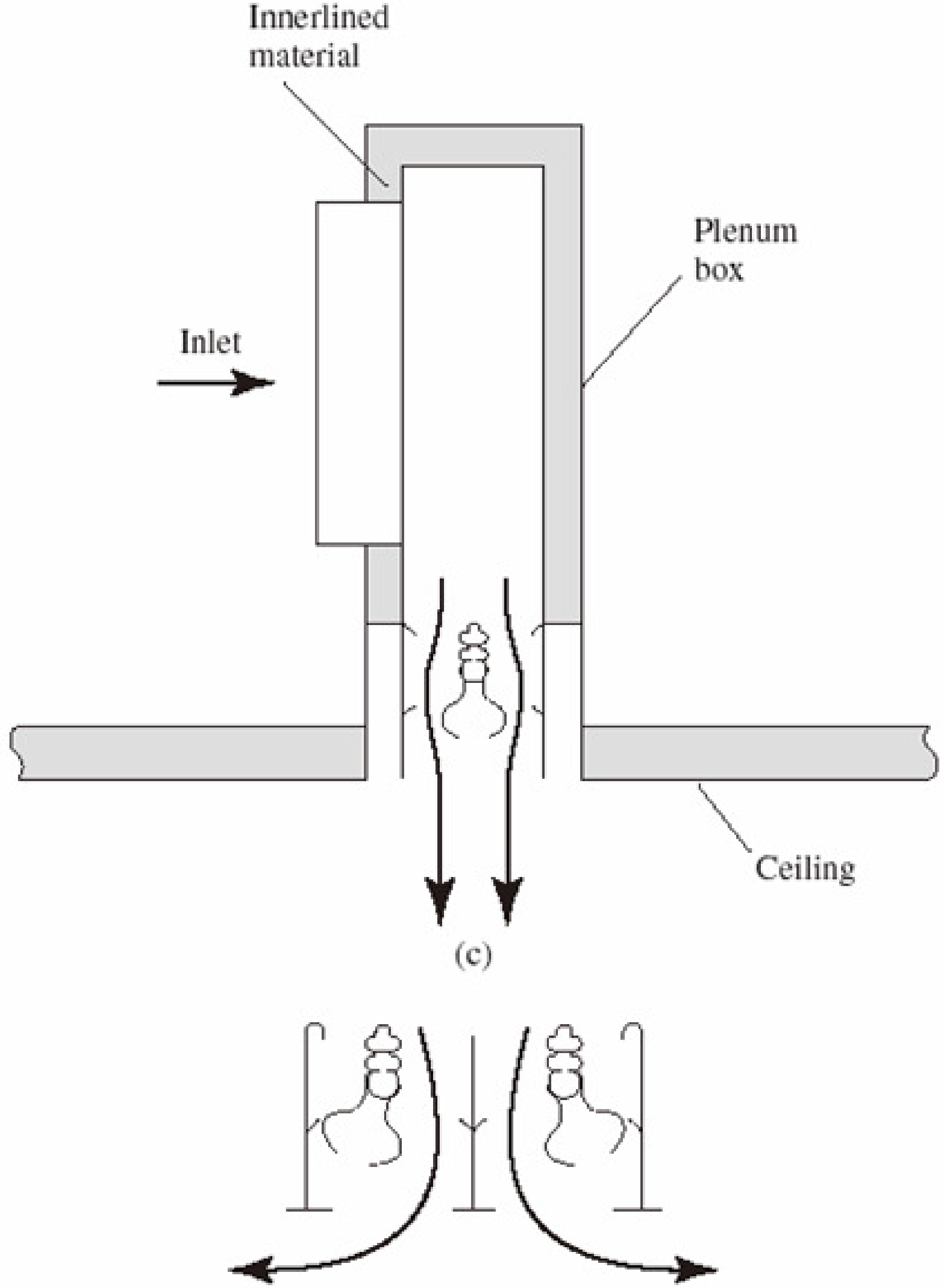


Perforated ceiling diffuser

(Source: *Wang, S. K., 2001. Handbook of Air Conditioning and Refrigeration*)

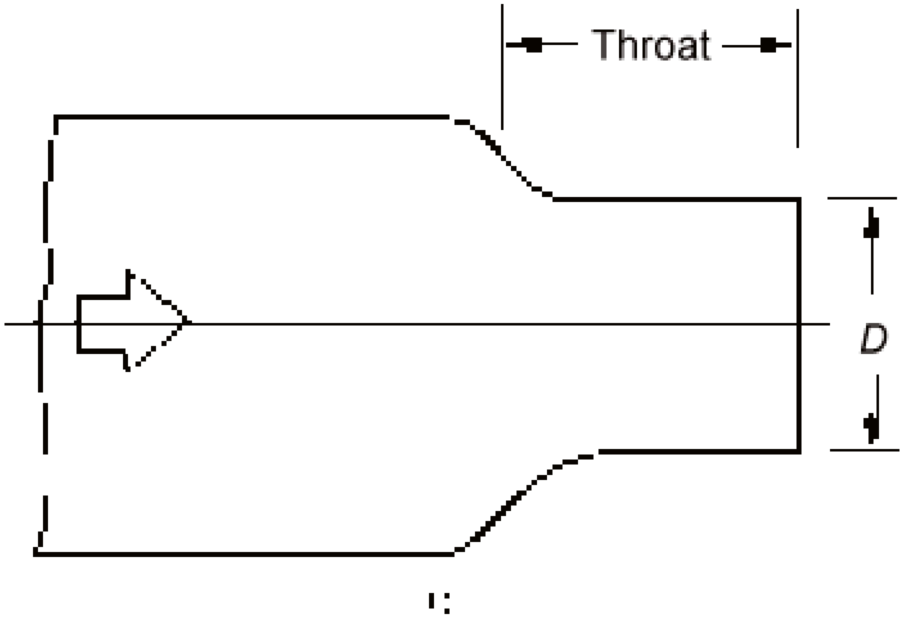
Slot diffusers



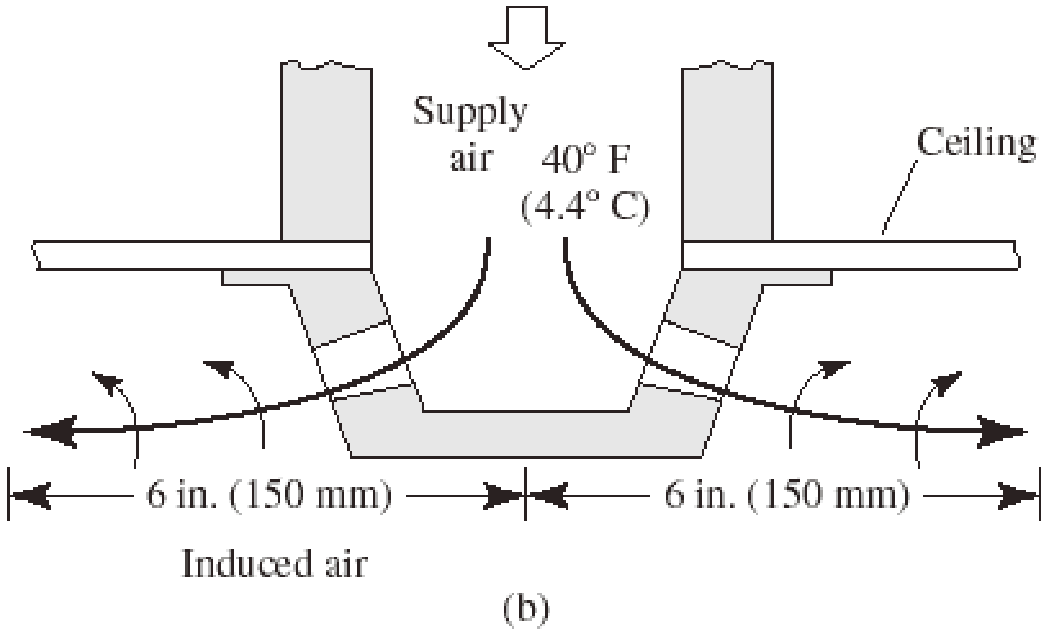


(Source: *Wang, S. K., 2001. Handbook of Air Conditioning and Refrigeration*)

Nozzle diffusers



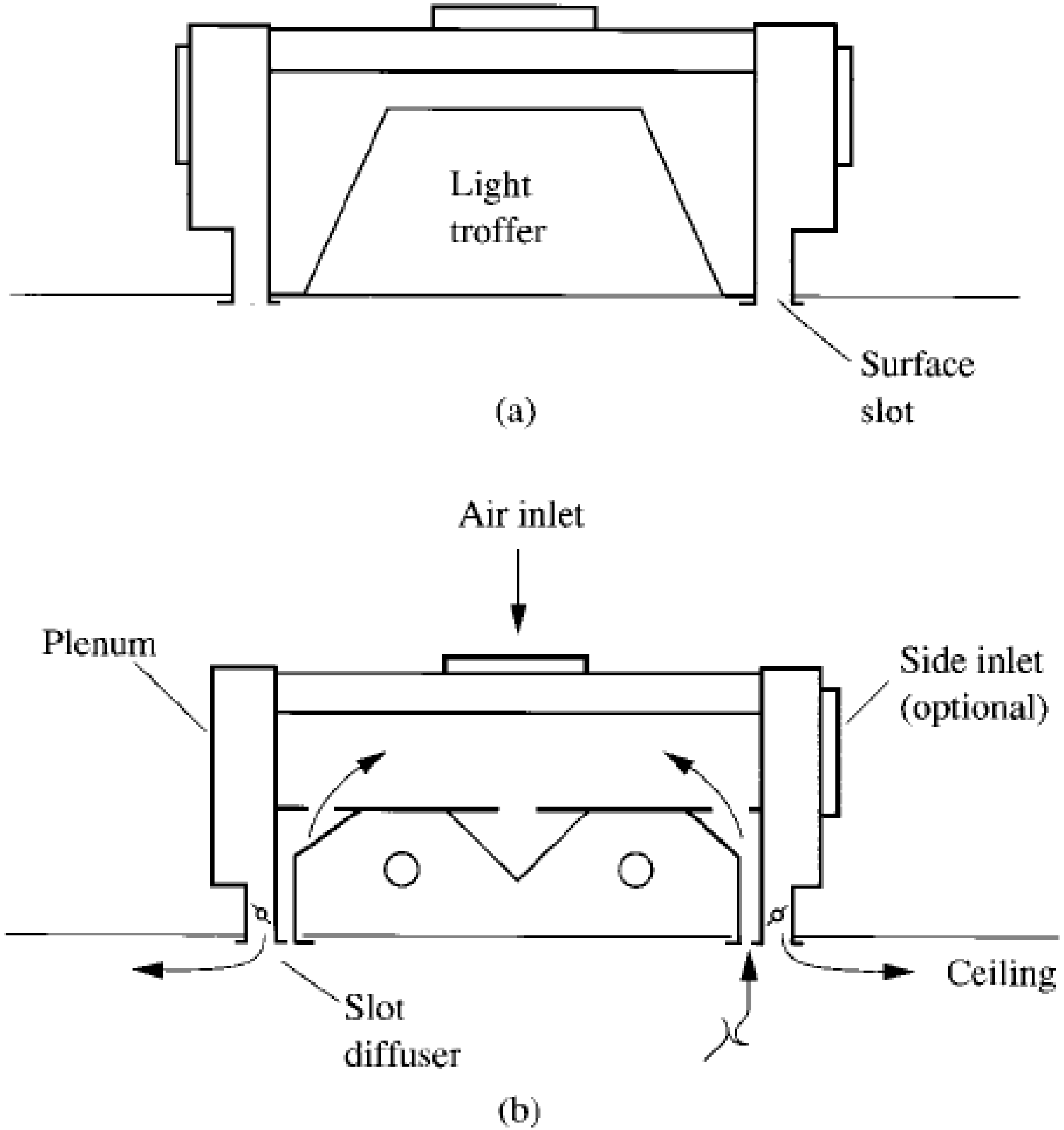
Round nozzle



Nozzle diffuser

(Source: *Wang, S. K., 2001. Handbook of Air Conditioning and Refrigeration*)

Light troffer, slot diffuser and return slot combination



(Source: *Wang, S. K., 2001. Handbook of Air Conditioning and Refrigeration*)