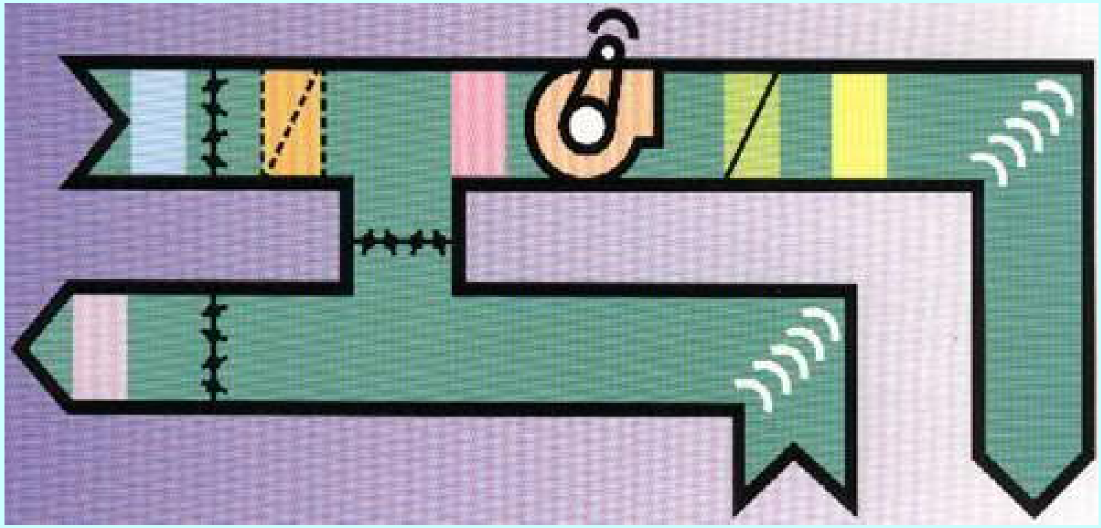
MEBS6008 Environmental Services II

http://www.mech.hku.hk/bse/MEBS6008/



# Space Air Diffusion I

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# Contents

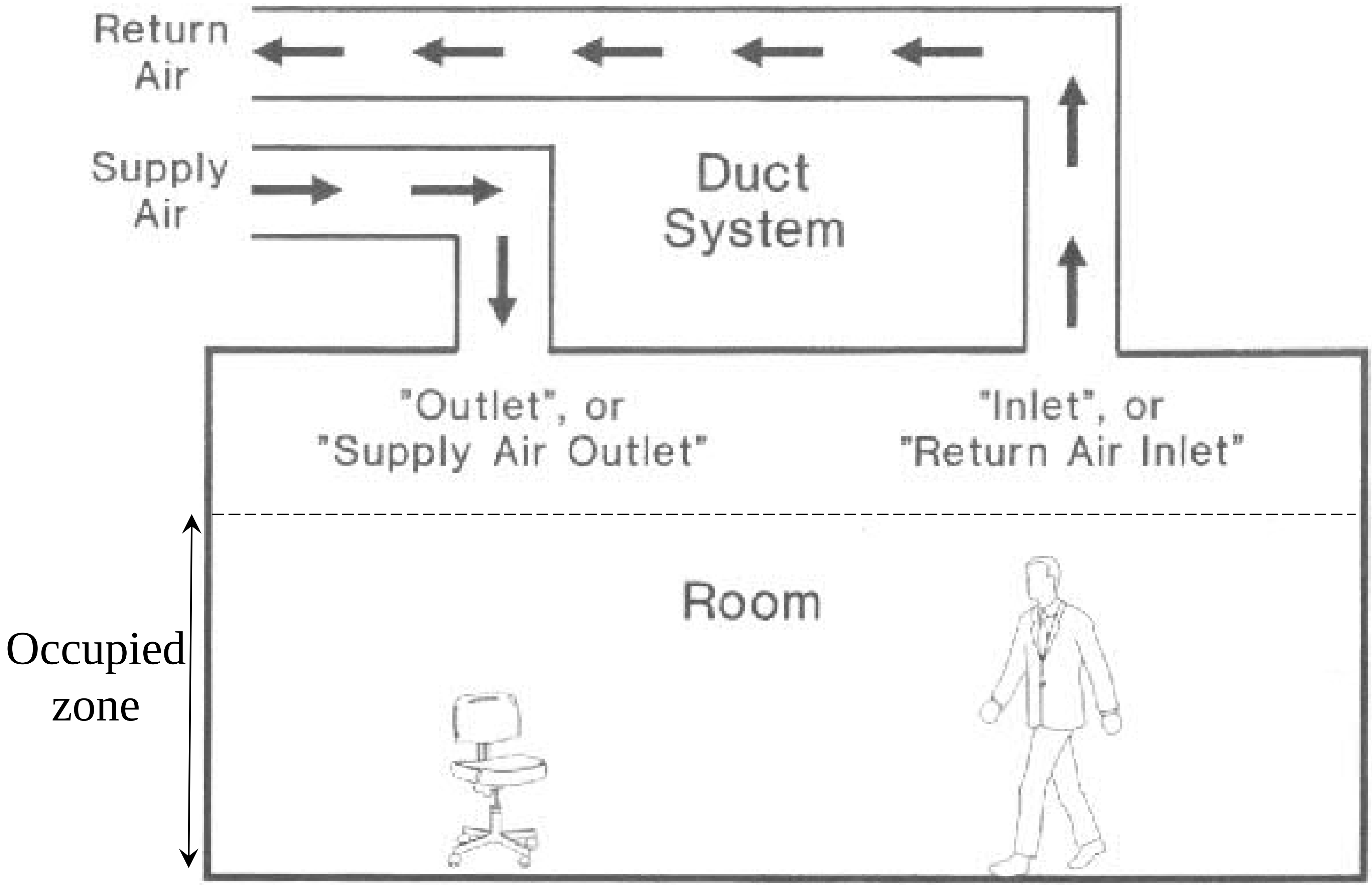
- Basic Principles
- Air Jets
- Outlets and Inlets
- Mixing Flow

# Basic Principles

- 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

# Basic Principles

- 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




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

# Basic Principles

Thermal Comfort

- Draft & effective draft temperature
  - Draft: unwanted local cooling of human body caused by air movement & lower space air temp.
  - Turbulence intensity, $I_{\text{tur}} = \sigma_v / v_m$
    - $\sigma_v$ = 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
    - $\theta = T_x - T_r - a\,(v_x - v_{rm})$

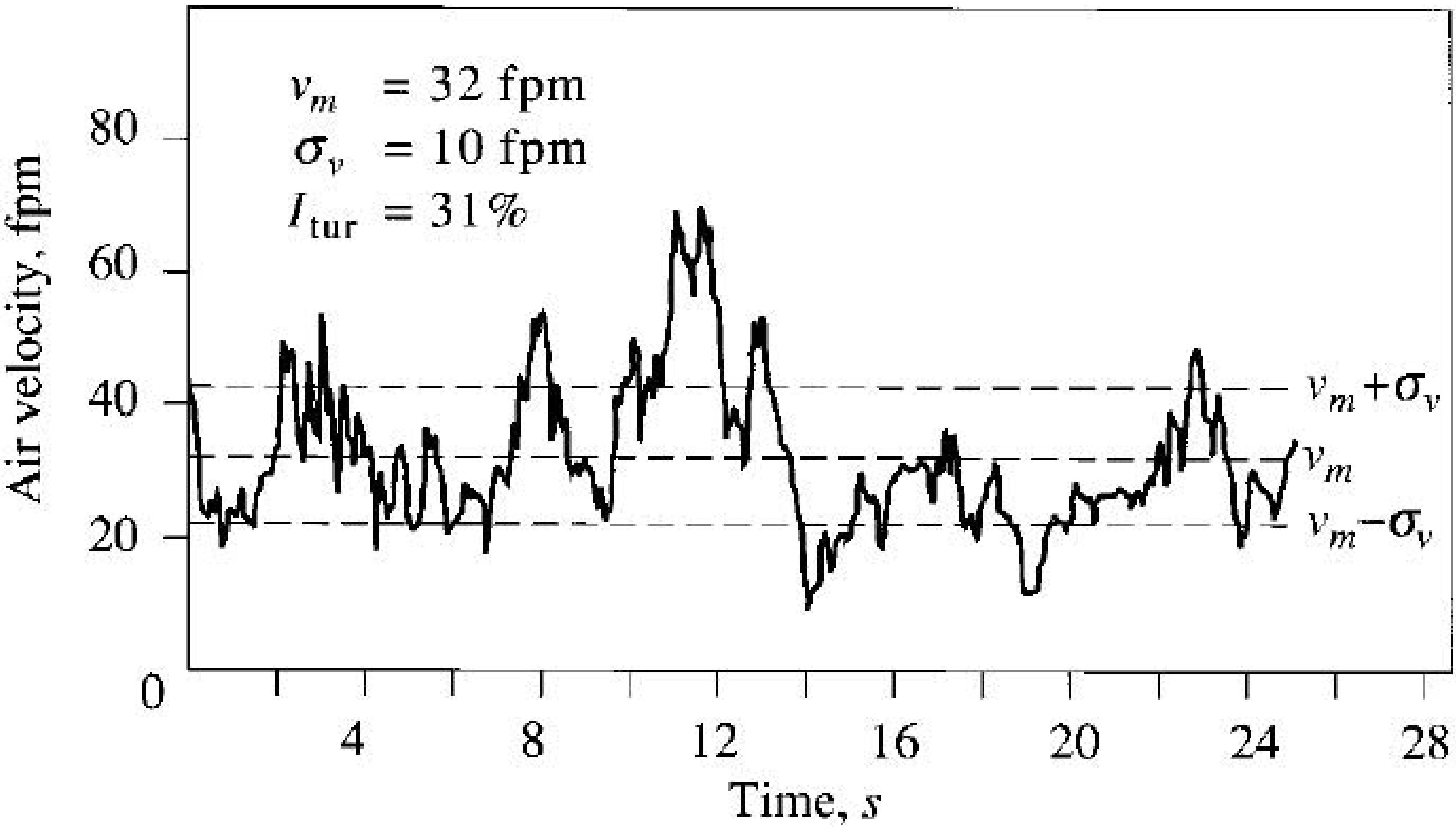



**FIGURE 18.1** Fluctuations of air velocity in a typical air conditioned space. (*Adapted with permission from ASHRAE Journal, April 1989, p. 30.*)

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

# Basic Principles

- Air diffusion performance index (ADPI)
  - ADPI = $(N_\theta \text{ x } 100) / N$
    - θ: effective draft temperature
    - $N_\theta$: number of points measured in occupied zone in which -1.7 °C < θ <1.1 °C
    - $N$ : 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 °C typical)

# Basic Principles

- 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

# Basic Principles

- 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 $\varepsilon = 1$; not so if $\varepsilon < 1$

# Basic Principles

- Ventilation effectiveness
  - Air system's ability to remove internally generated contaminants from a zone, space or building
- Age of air $\theta_{age}$ (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

# Basic Principles

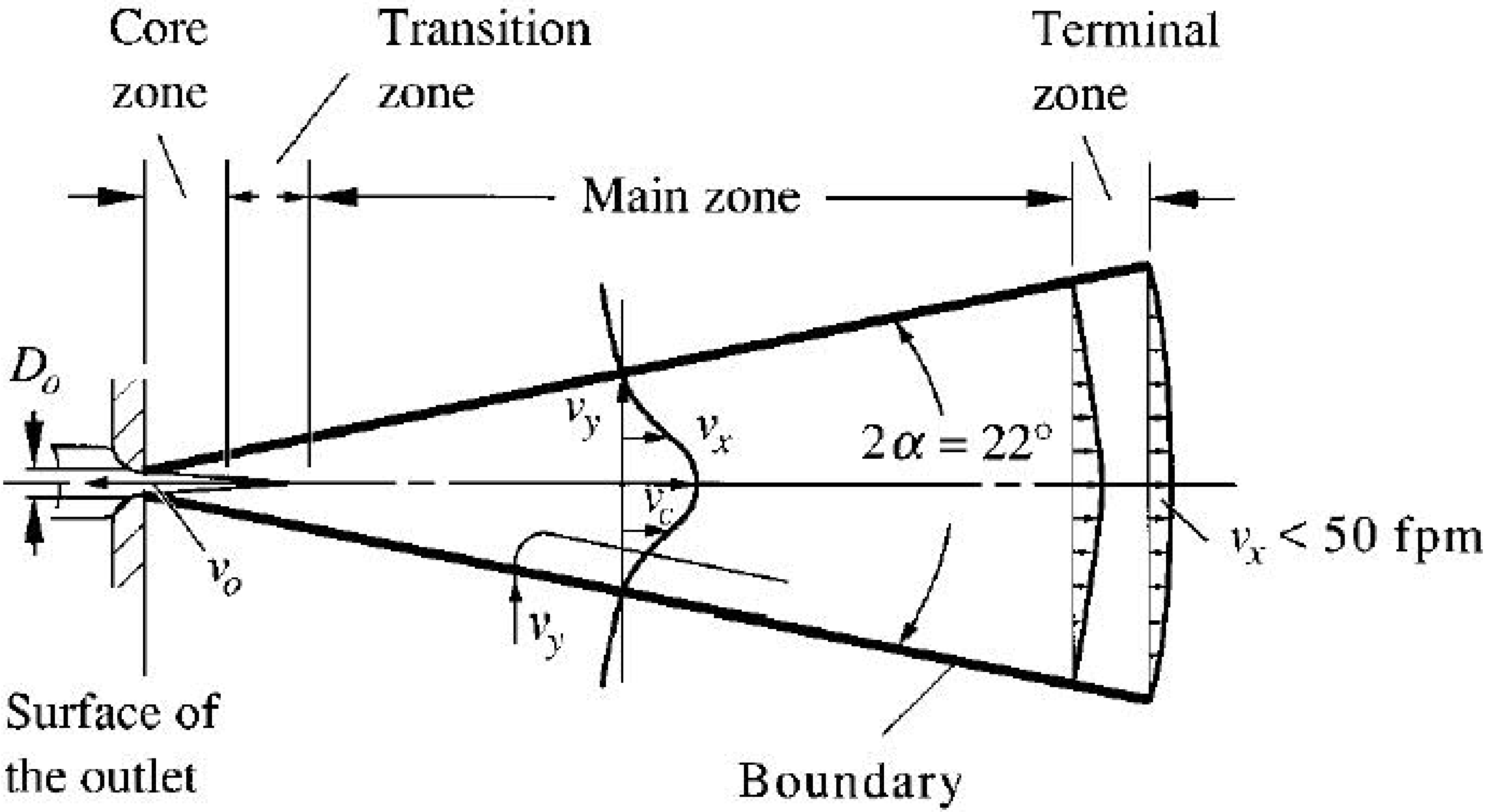
- Air change effectiveness $\varepsilon_N$
  - Air system's ability to deliver ventilation air
    - How well outdoor air is diffused to various locations
  - $\varepsilon_N = \tau_N / \theta_{age,\, N}$
    - $\tau_N$ : nominal time constant (min. or hr.)
      - ACH = supply volume flow rate / space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

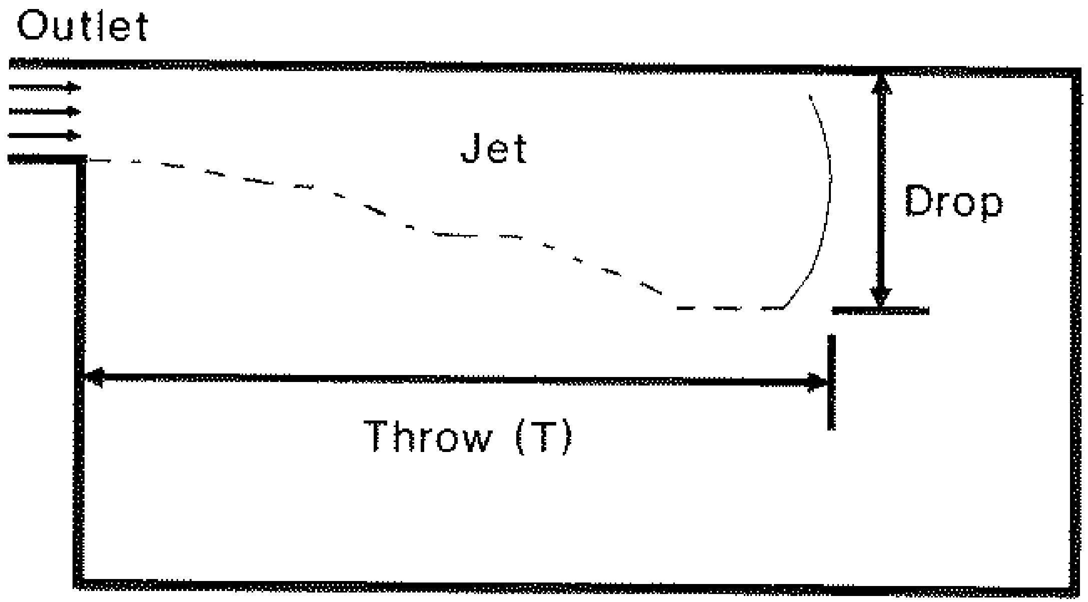



Four zones of a free, isothermal, axial air jet

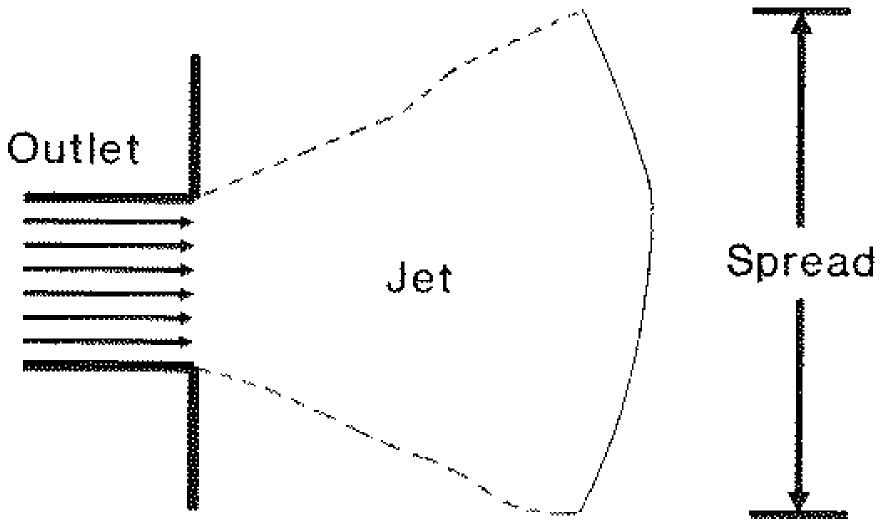
(Source: *Wang, S. K., 2001. Handbook of Air Conditioning and Refrigeration*)

# 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

- Characteristic length, *L*
  - Horizontal distance from outlet to the nearest vertical opposite wall, or to the midplane between 2 outlets in the direction, OR the distance to the closest intersection of air jets
  - Ratio of $T_v$/L is related to ADPI of various supply outlets and has been used a parameter in space diffusion design

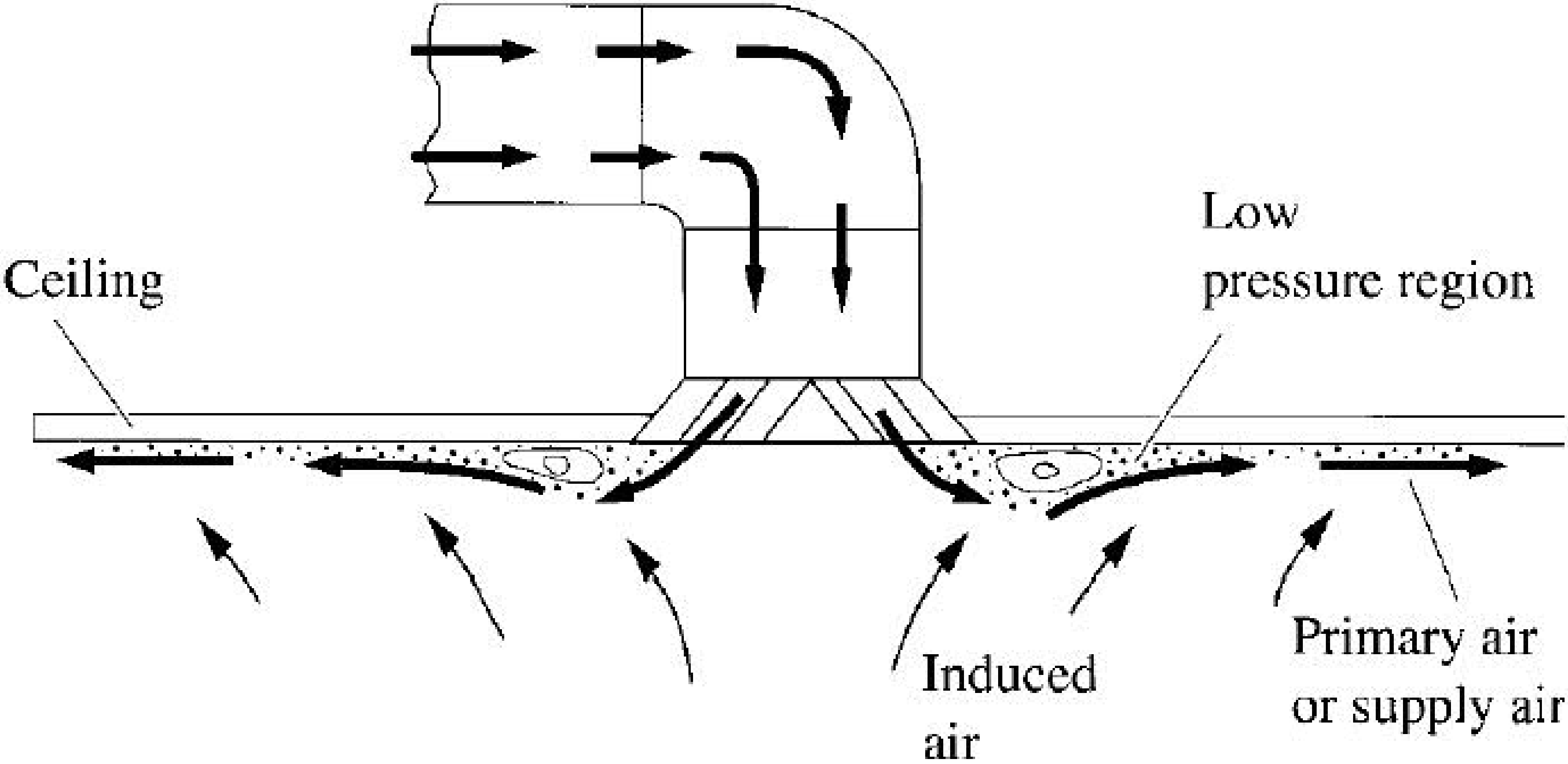
**Table 3. Characteristic Length for Various Diffuser Types**

| Diffuser Type | Characteristic Length, L |
|---|---|
| High Sidewall Grille | Distance to wall perpendicular to jet |
| Circular Ceiling Diffuser | Distance to closest wall or intersecting air jet |
| Sill Grille | Length of room in the direction of the jet flow |
| Ceiling Slot Diffuser | Distance to wall or midplane between outlets |
| Light Troffer Diffusers | Distance to midplane between outlets, plus distance from ceiling to top of occupied zone |
| Perforated, Louvered Ceiling Diffusers | Distance to wall or midplane between outlets |

(Source: http://www.price-hvac.com)

# Air Jets

- Confined air jets (in practical cases)
  - Surface effect (or Coanda 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 Coanda effect)

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

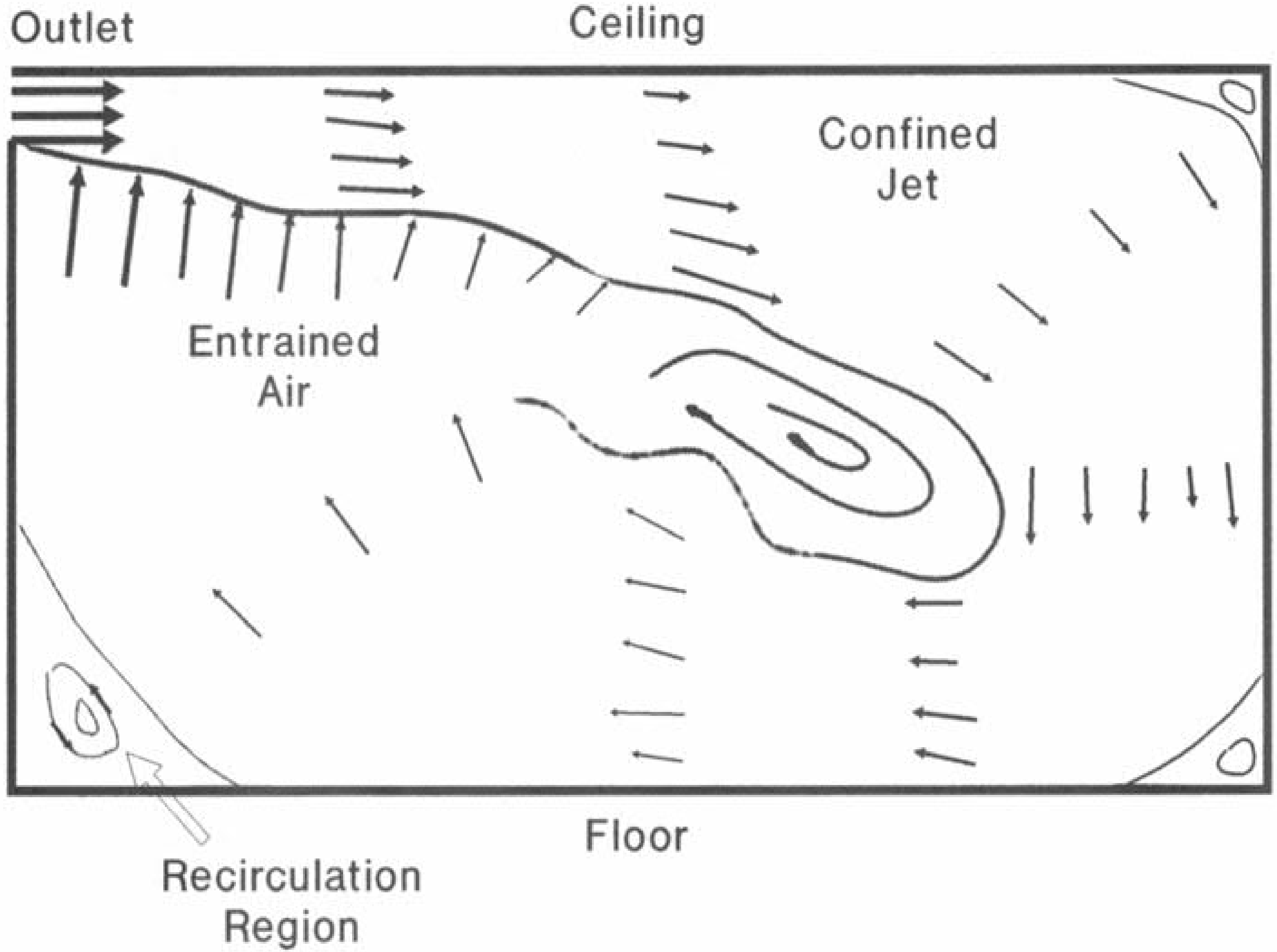
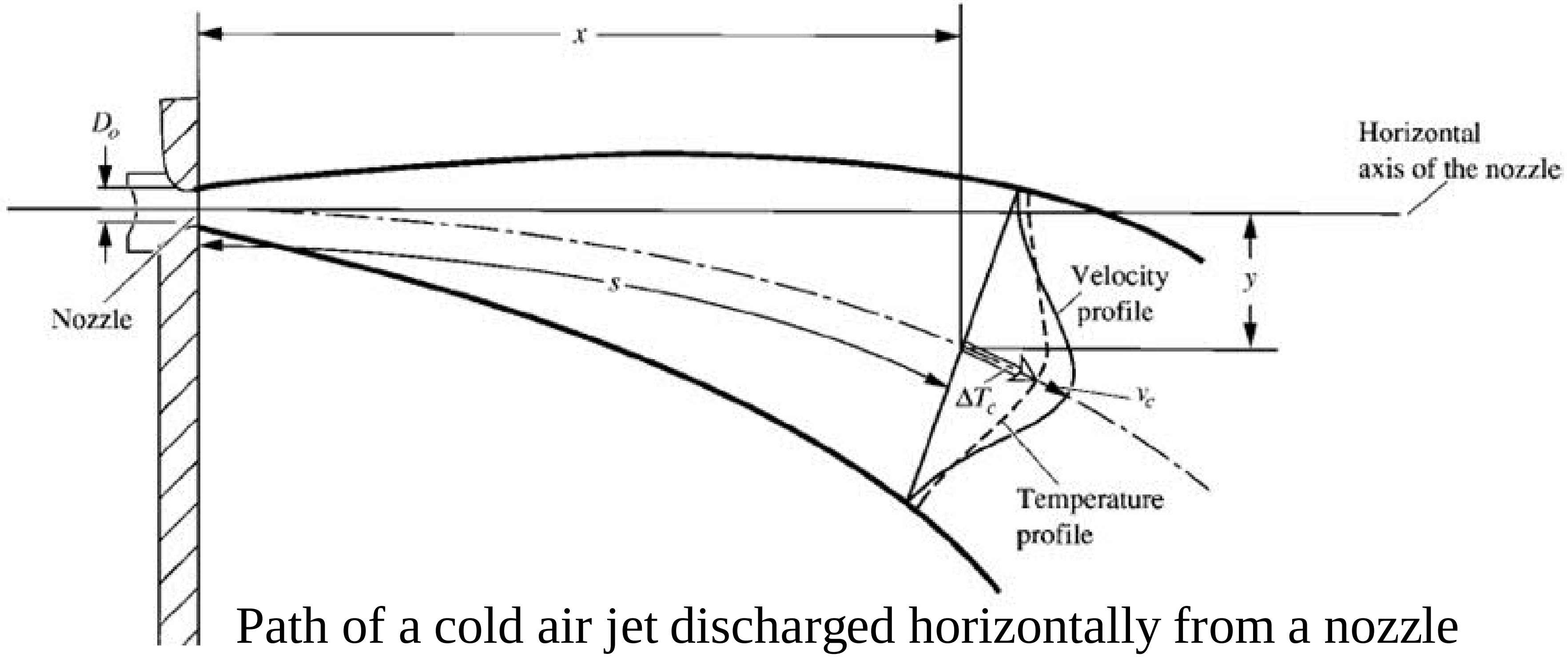



***Figure 5.11*** *Because a real room has a limited volume, a jet's growth and shape are affected. A "confined jet" is the result.*

(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

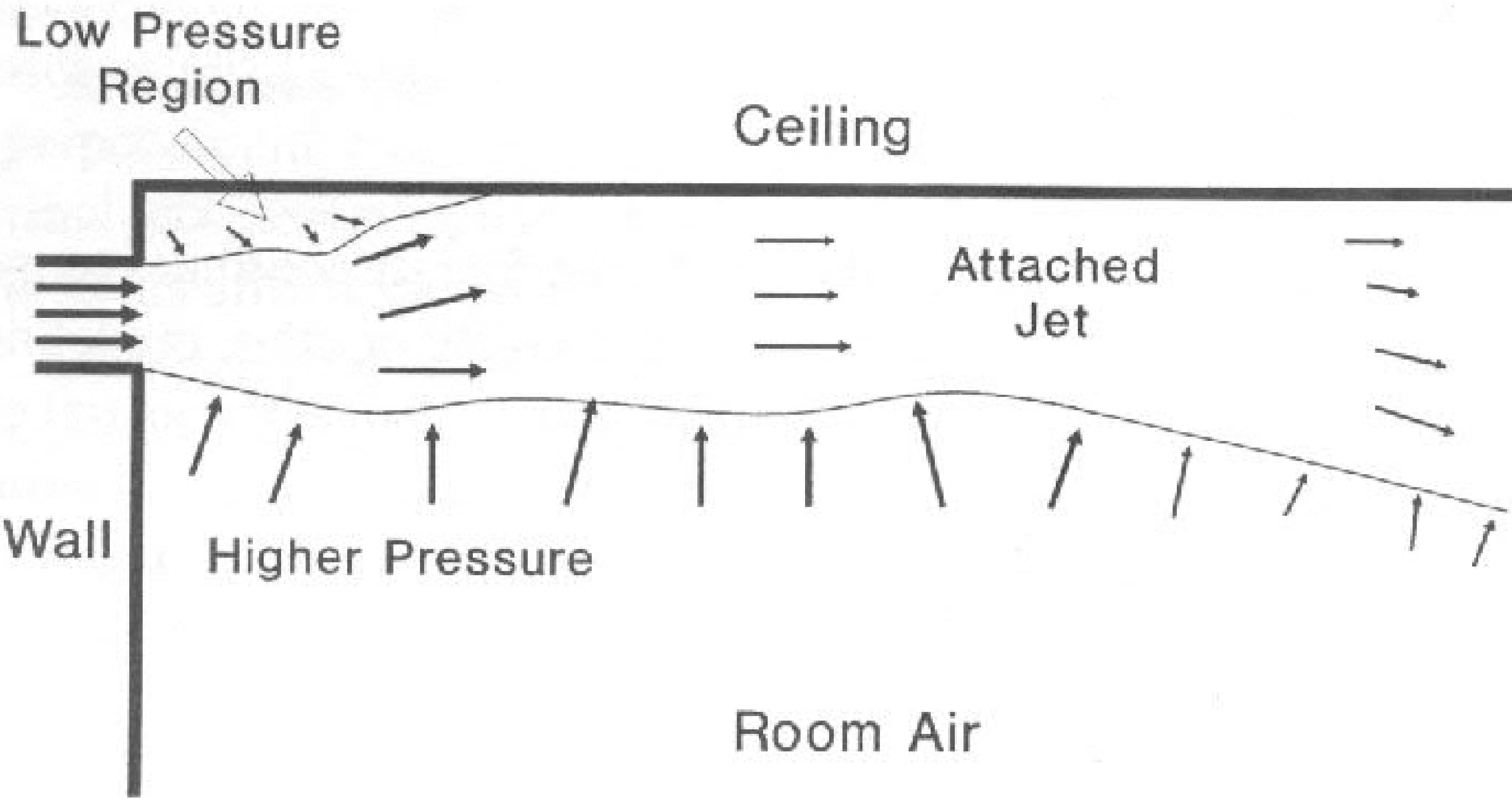



***Figure 5.9*** *A jet attaches to a surface like a ceiling because entrainment is limited on that side.*

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

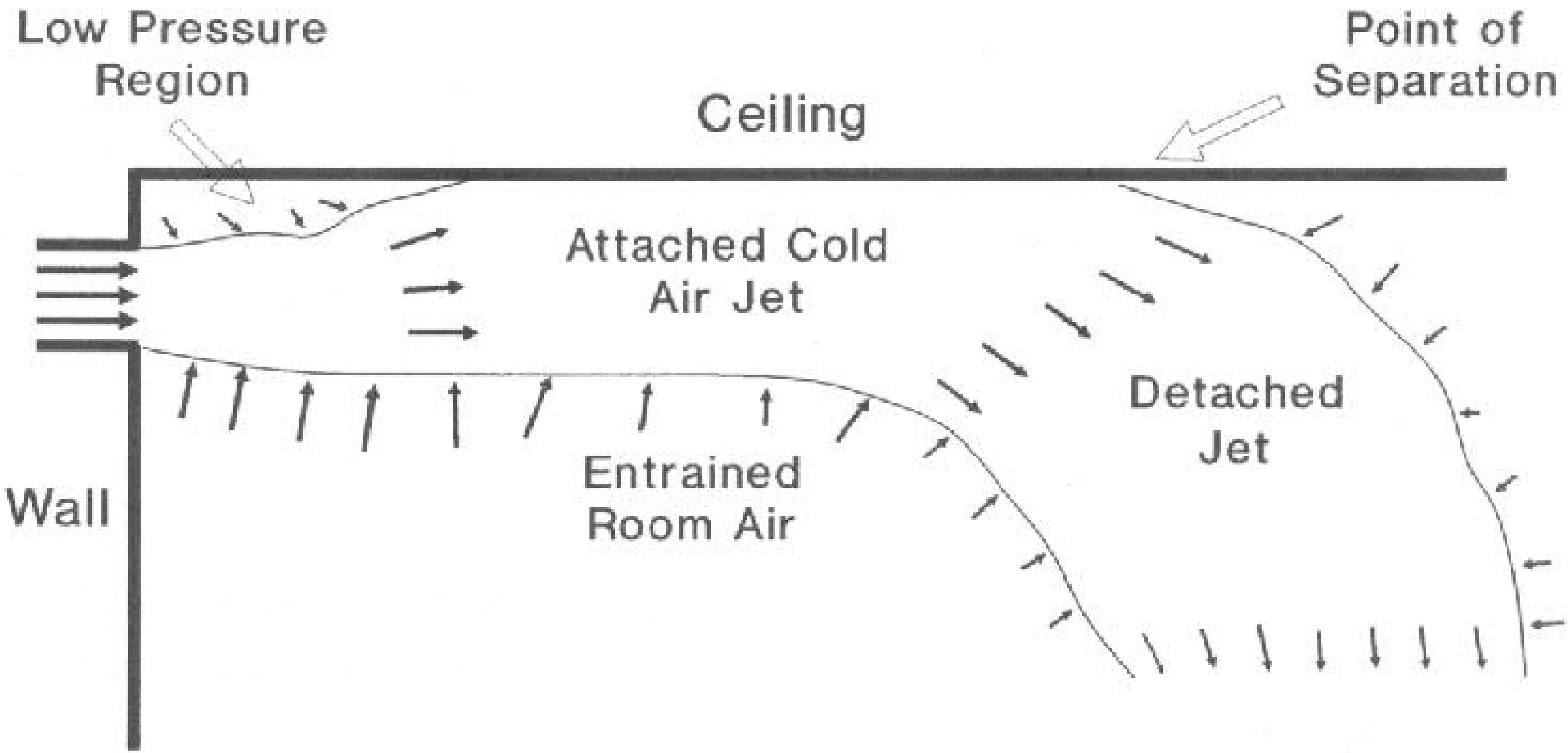



***Figure 5.10*** *If a cool air ceiling jet slows to the point that negative buoyancy overcomes the force causing attachment, the jet detaches from the ceiling.*

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

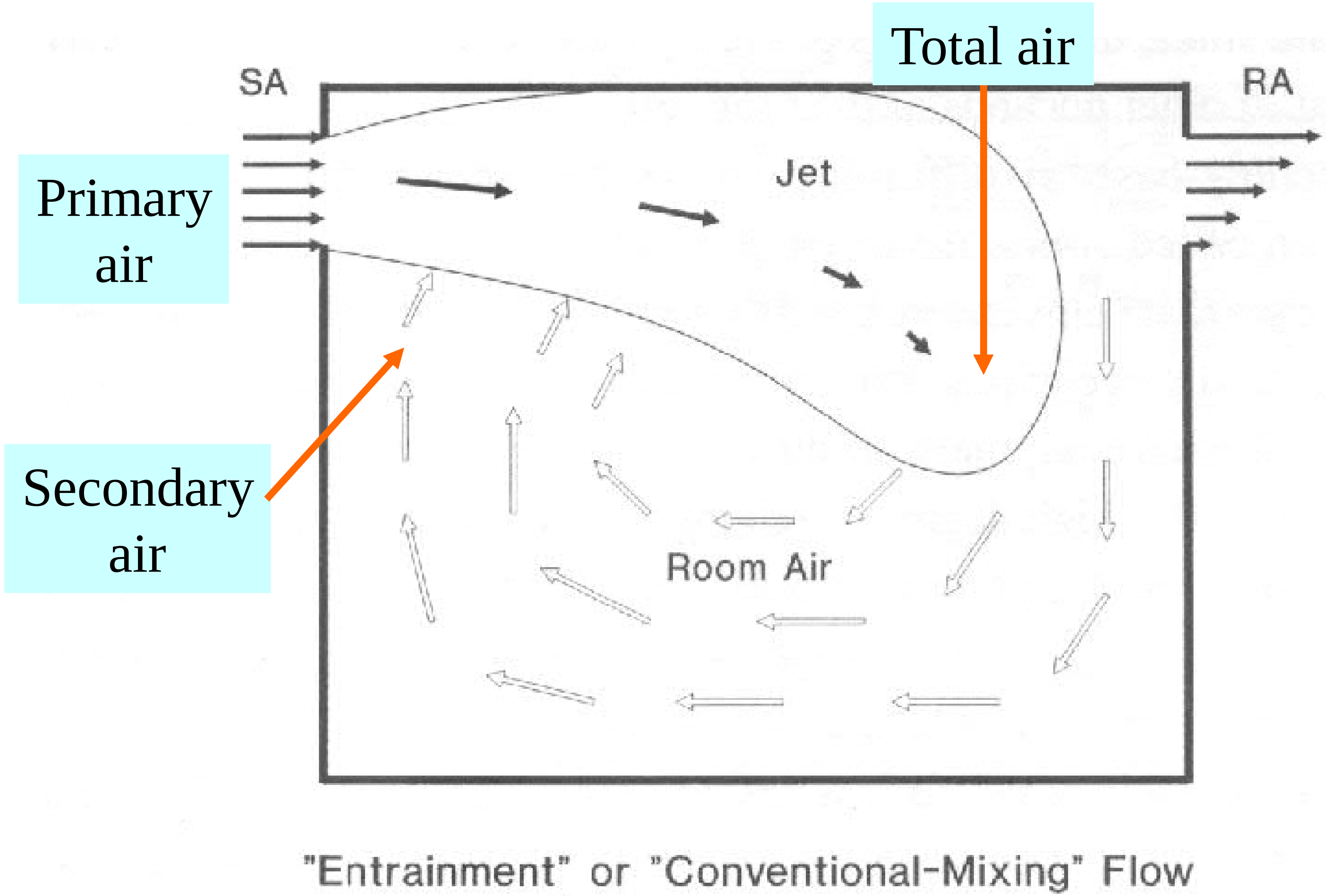



***Figure 6.2*** *Real airflows in rooms are most often "entrainment flow" or "conventional mixing" where confined jets and surfaces affect the resulting pattern.*

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

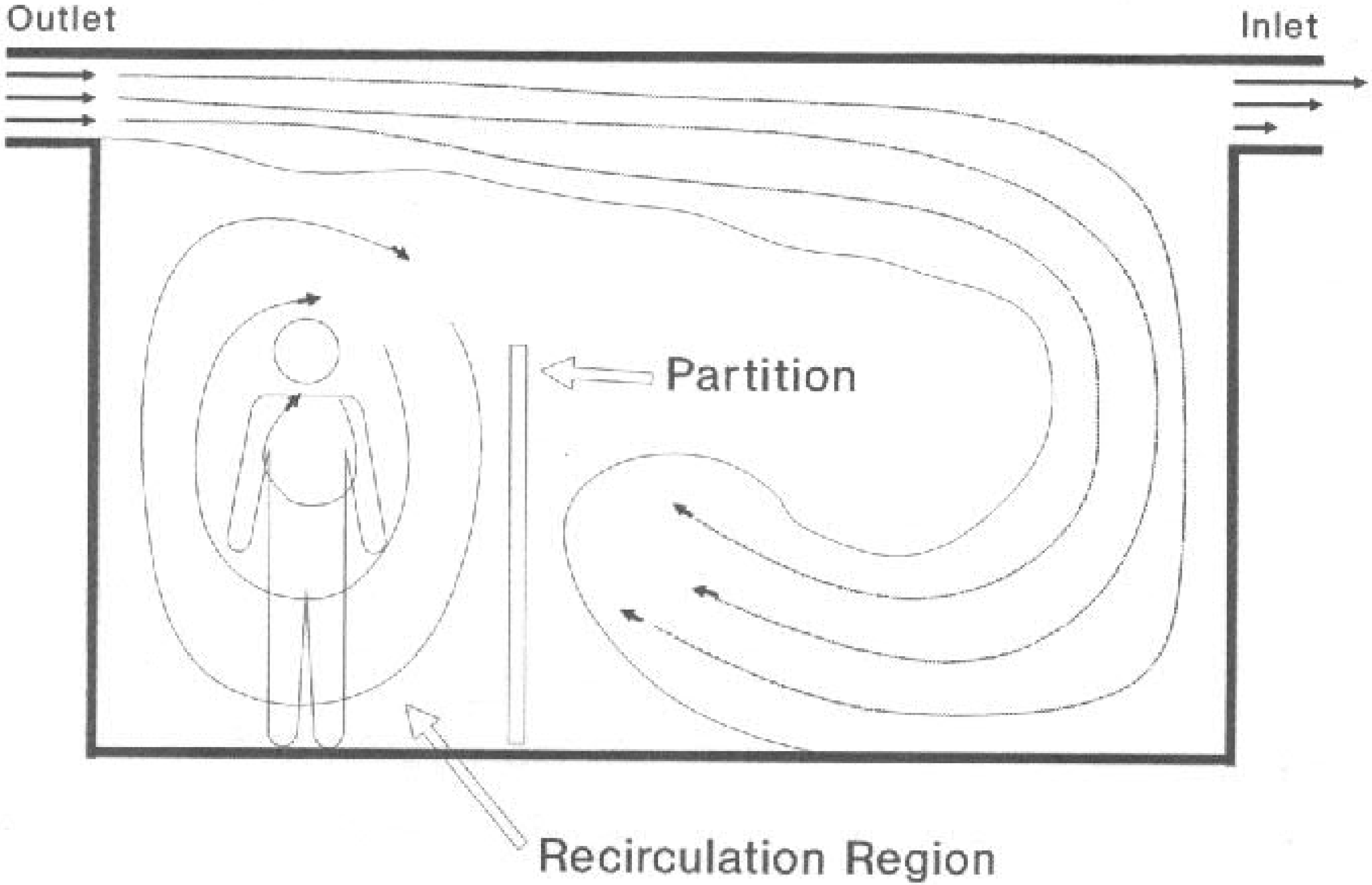



***Figure 6.3*** *Recirculation regions often form due to limiting objects and surfaces within spaces, or the characteristics of the jet and the room.*

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

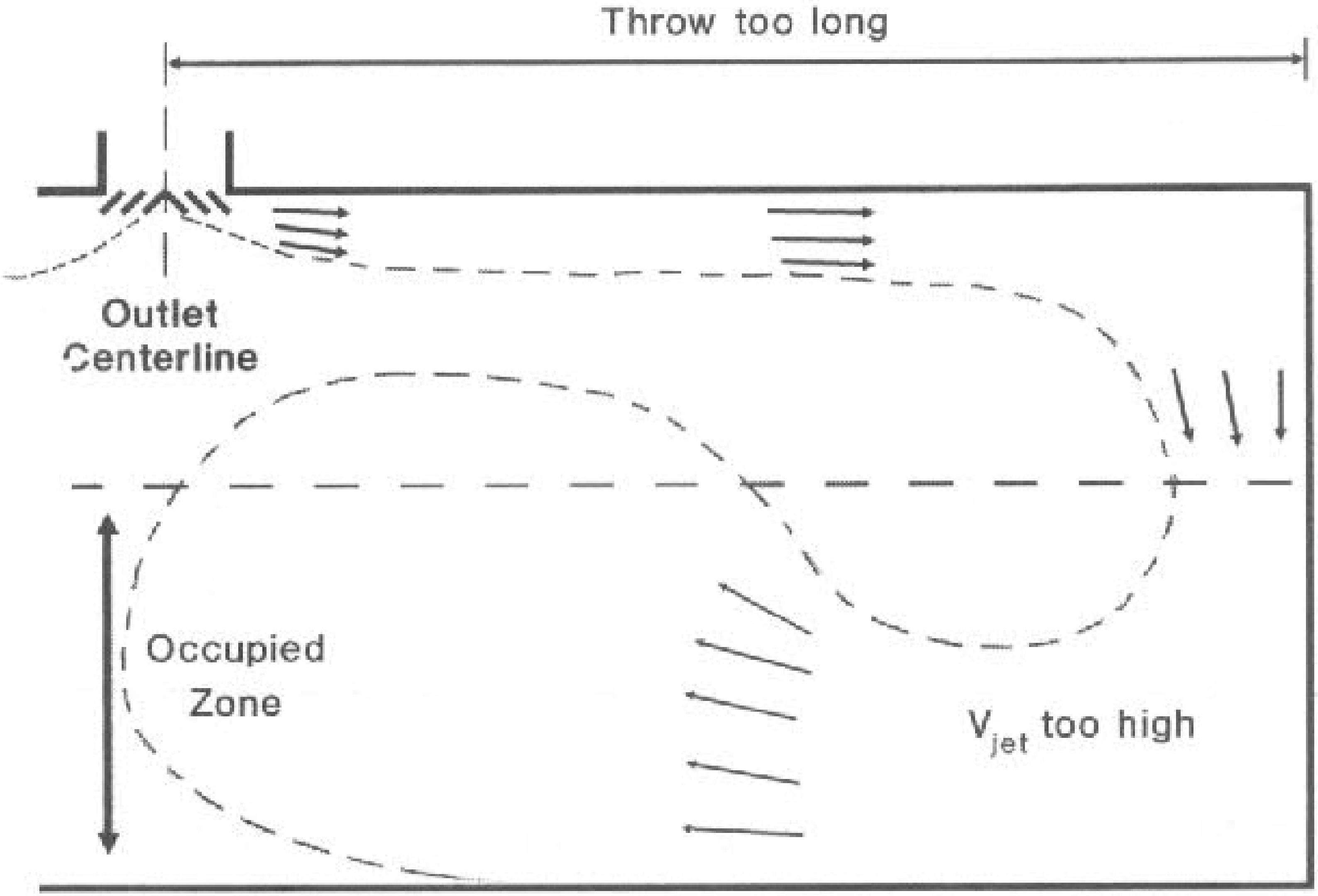



***Figure 6.9*** *When a jet's throw is too long, the velocity and the temperature of the air entering the occupied zone may be objectionable.*

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

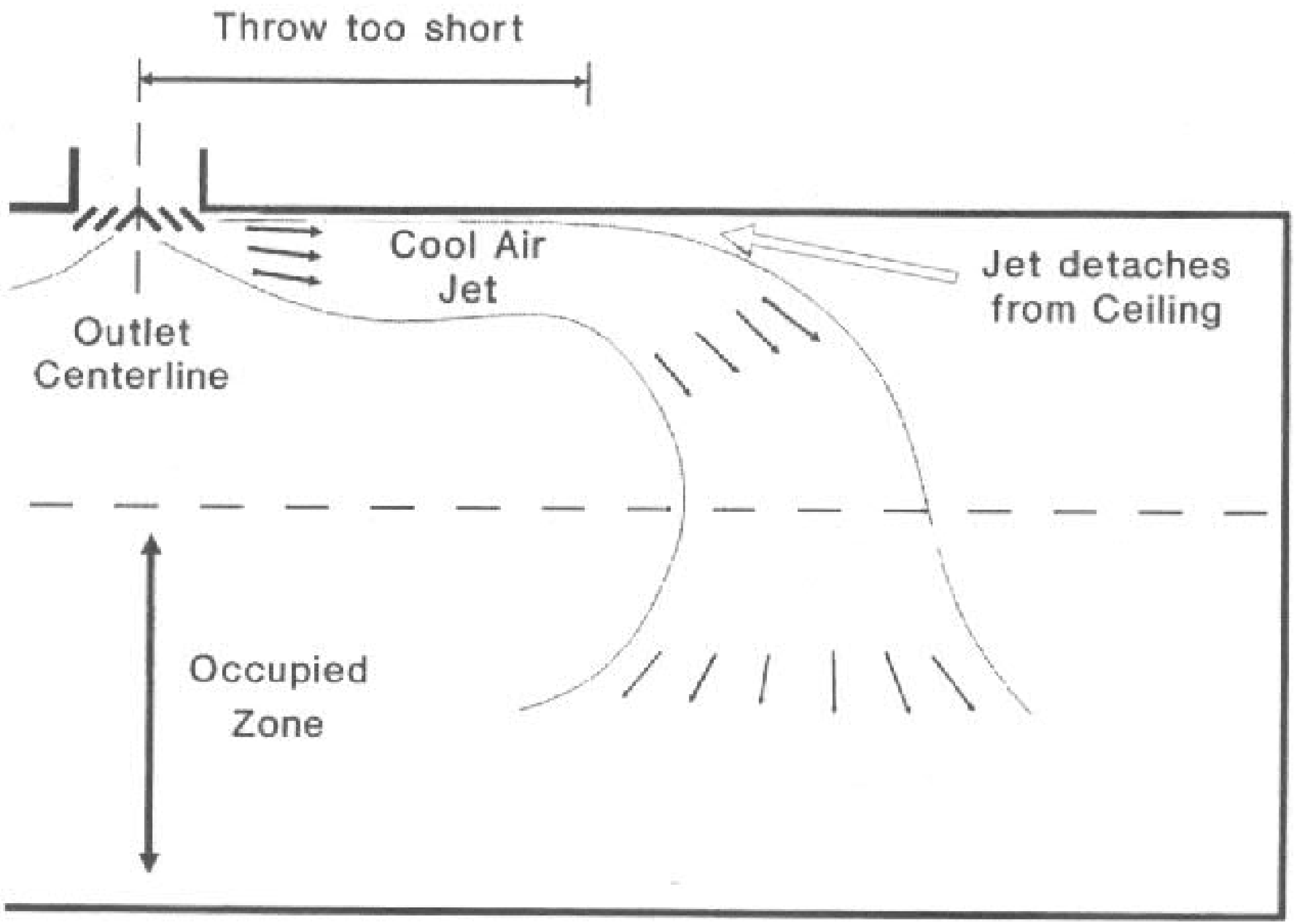



***Figure 6.10*** *"Dumping" is when a jet enters the occupied zone and is objectionable. Detachment is one potential cause of dumping, and can be created by too little airflow and/or an oversized outlet.*

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

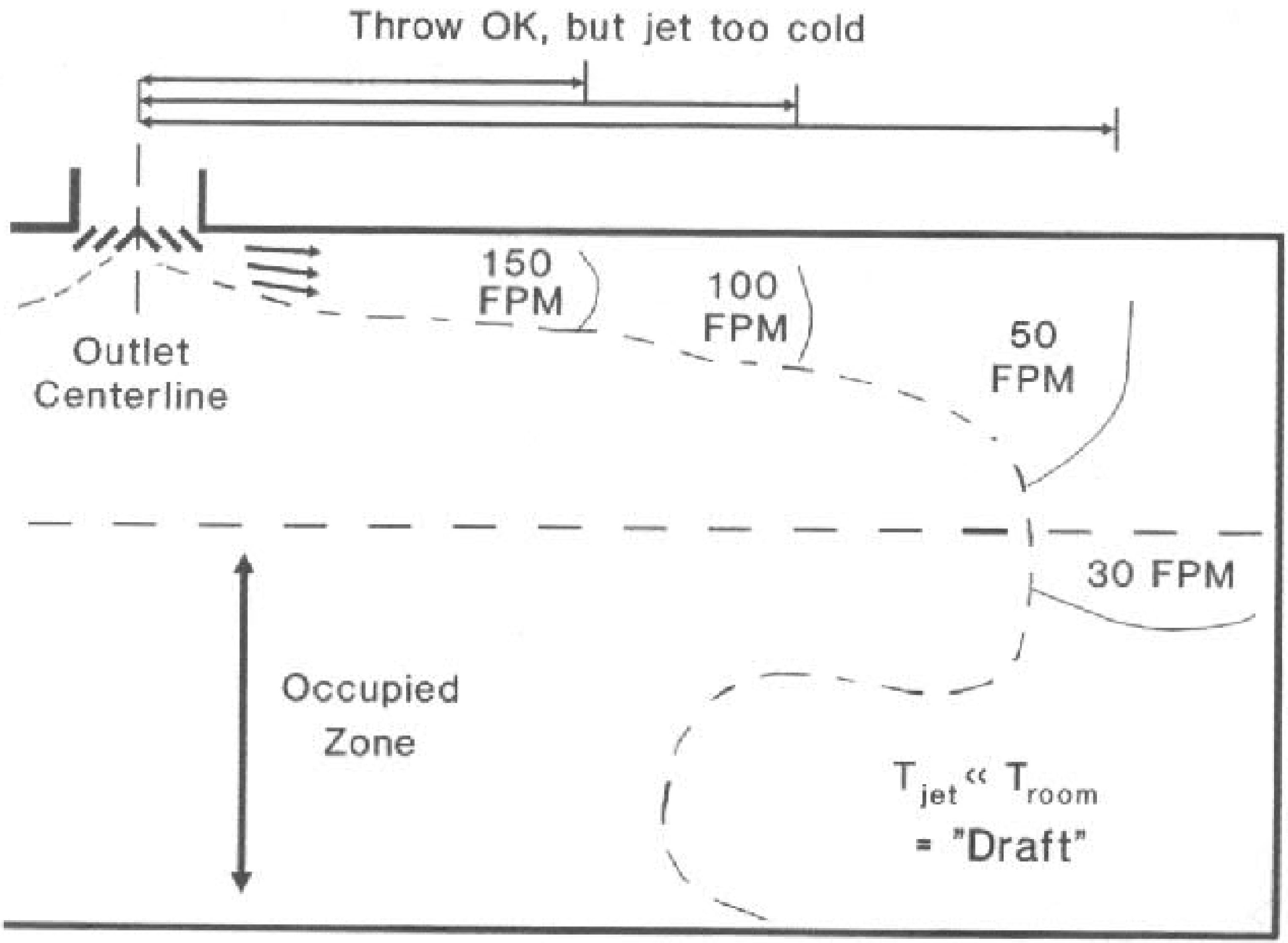
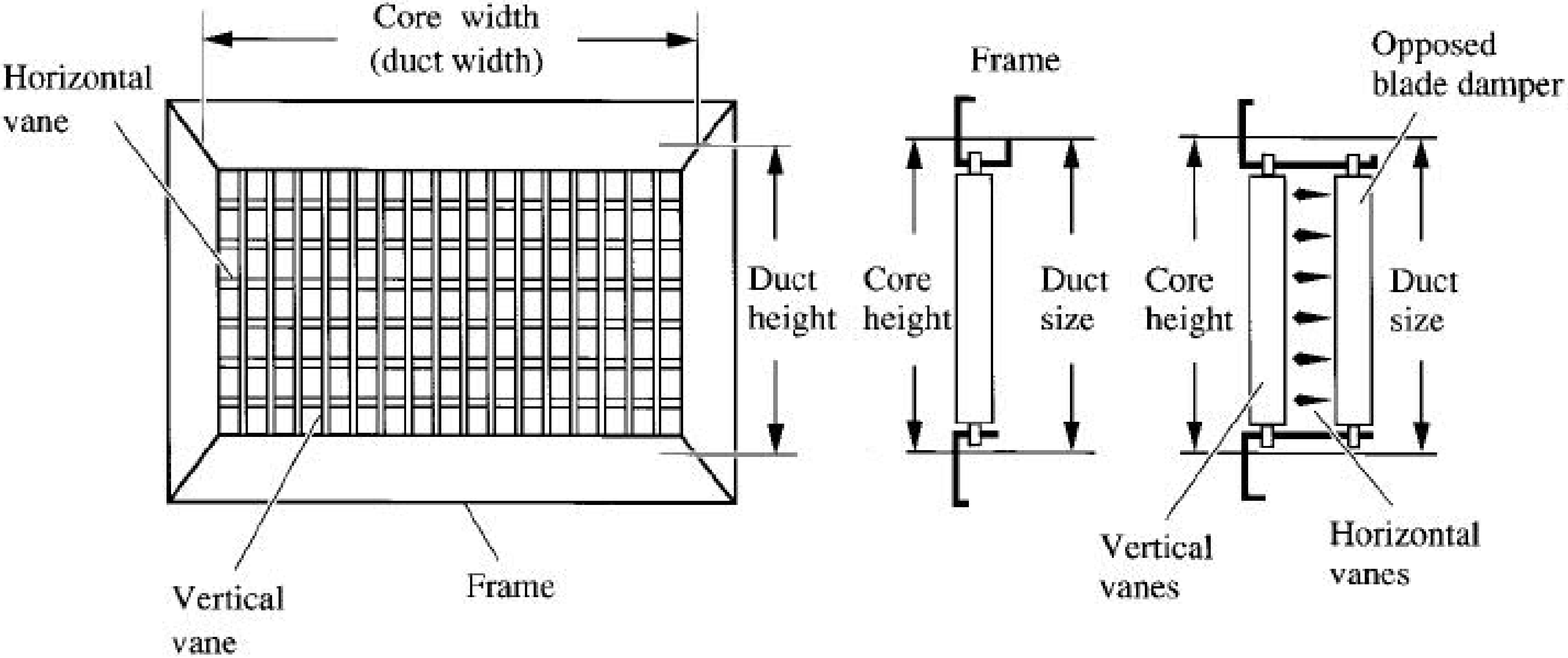



***Figure 6.11*** *Even if velocities are acceptable, too large a temperature difference between the jet and the room air can also cause "draft" complaints.*

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

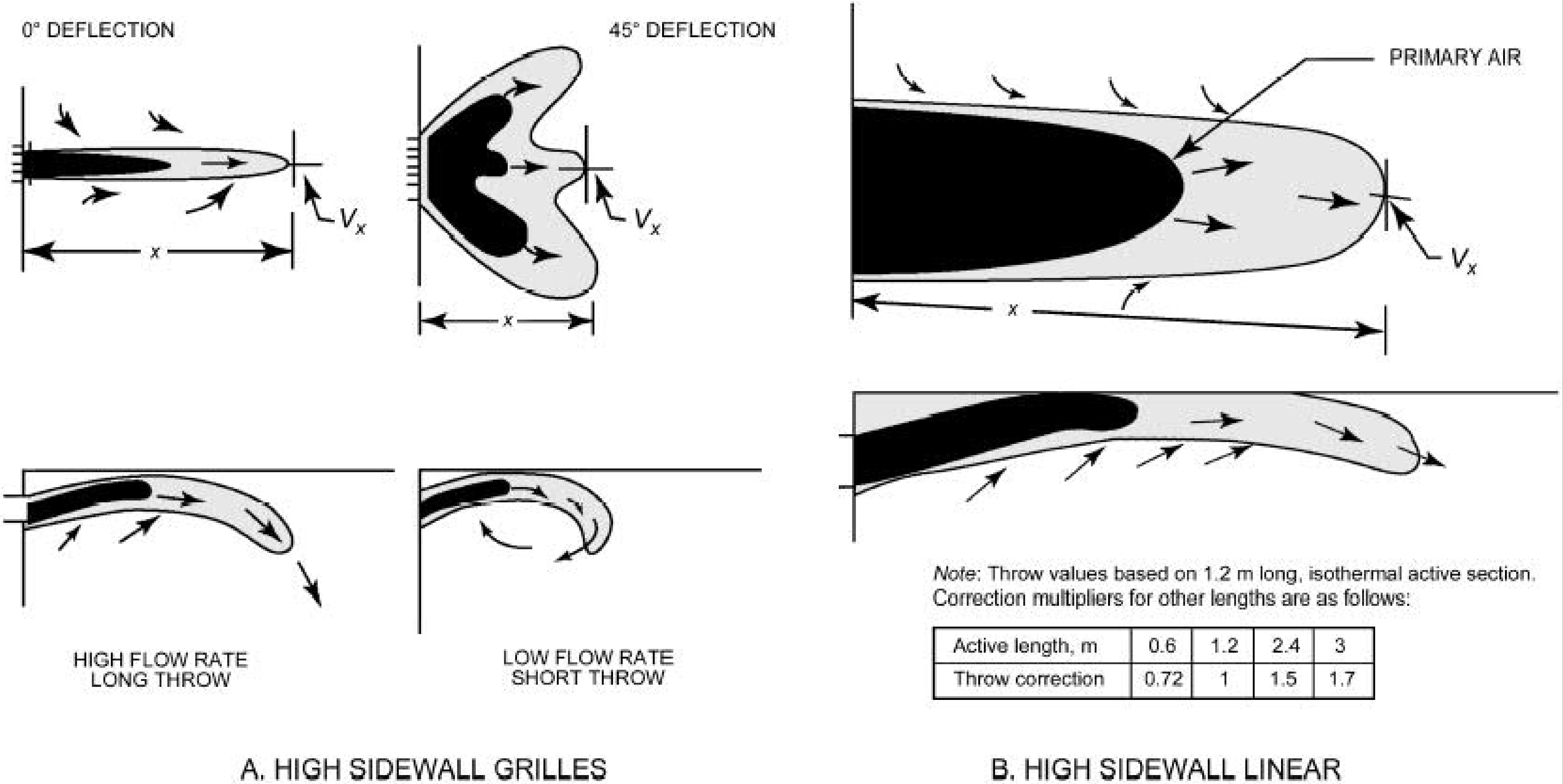
# Outlets and Inlets

- 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




Supply grille and register

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




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

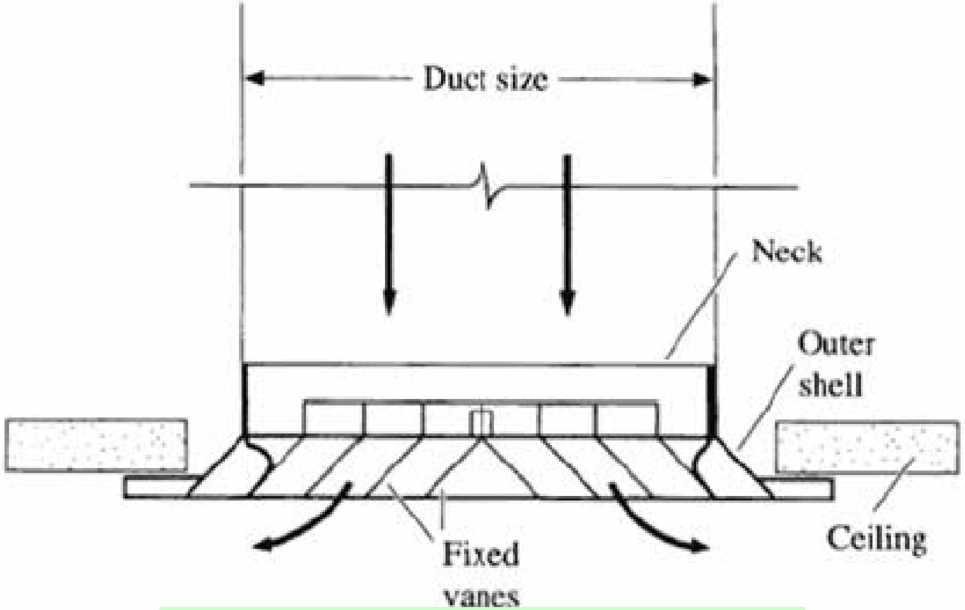
| Active length, m | 0.6 | 1.2 | 2.4 | 3 |
|---|---|---|---|---|
| Throw correction | 0.72 | 1 | 1.5 | 1.7 |

# Airflow patterns of high sidewall supply grilles

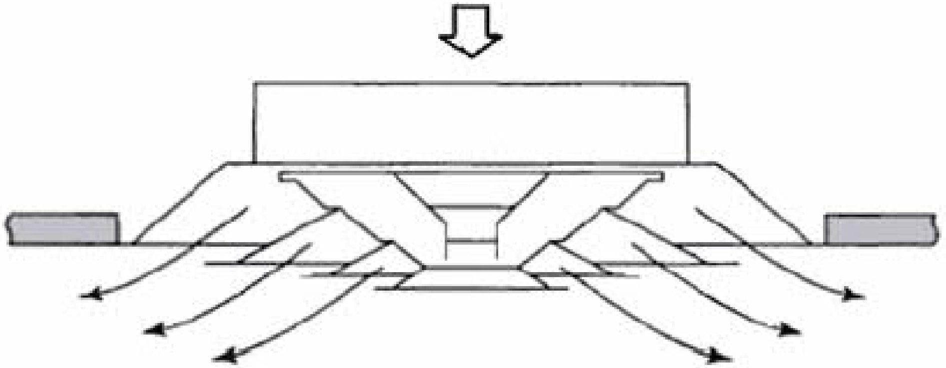
(Source: *ASHRAE Handbook Fundamentals 2001*)

# Outlets and Inlets

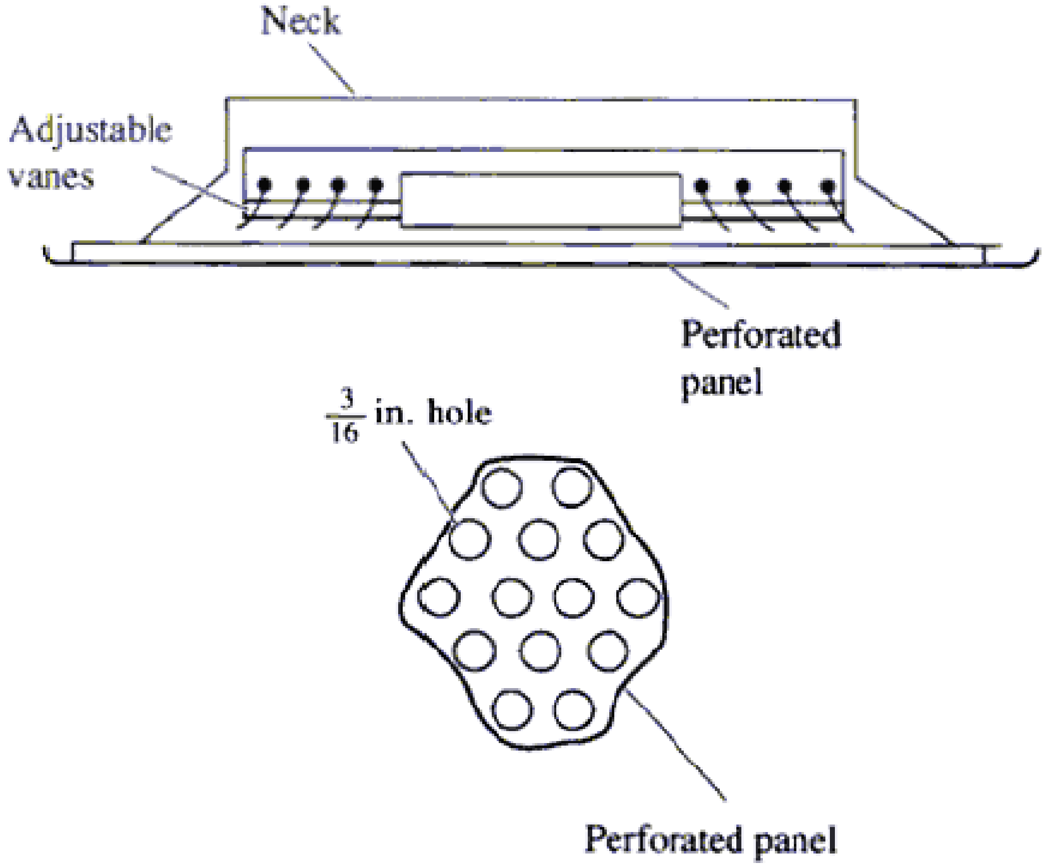
- Performance data of grilles and registers
  - Core size or core area
  - Volume flow rate
  - Air velocity
  - Total pressure loss
  - Throw at various terminal velocities
  - Noise criteria curve




Square & rectangular



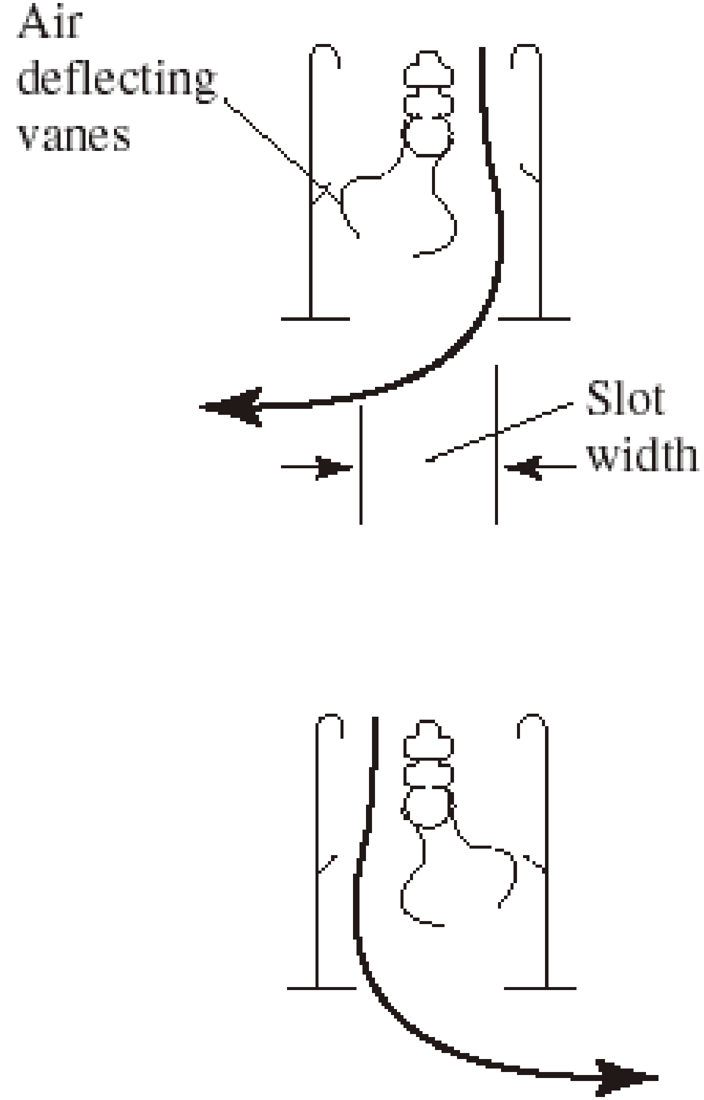
Removable inner-core

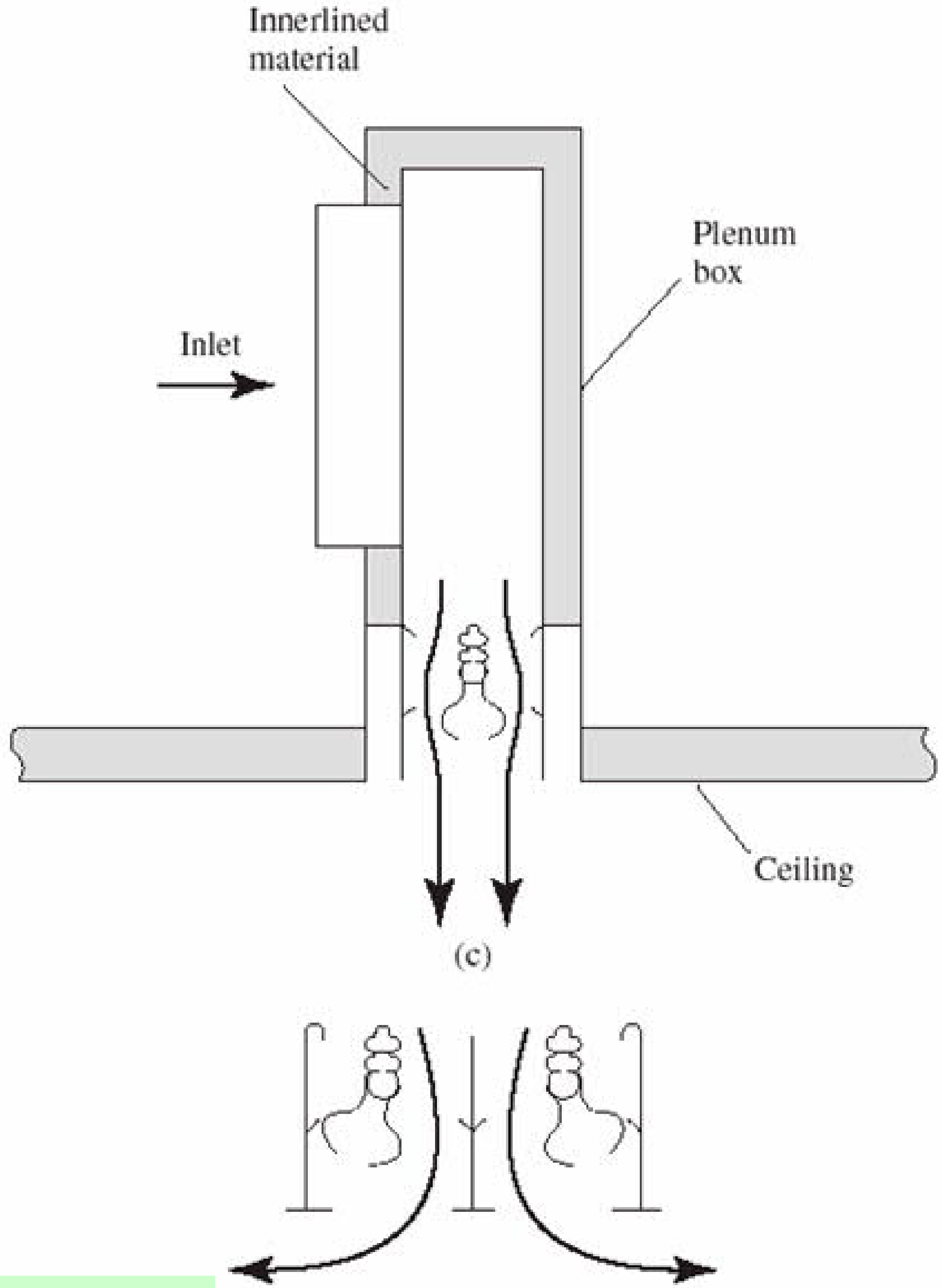



Perforated ceiling diffuser

# Ceiling diffusers

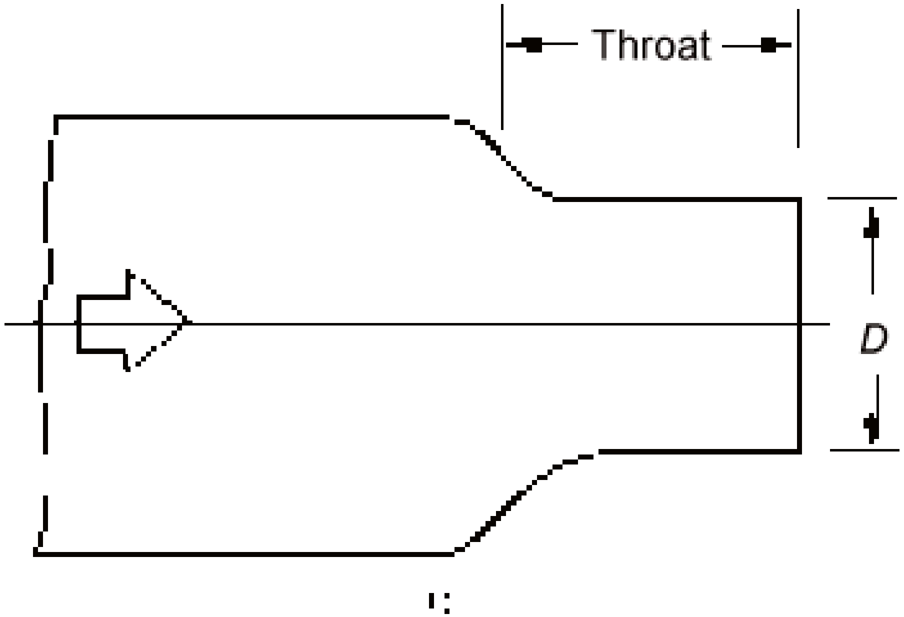
(Source: *Wang, S. K., 2001. Handbook of Air Conditioning and Refrigeration*)



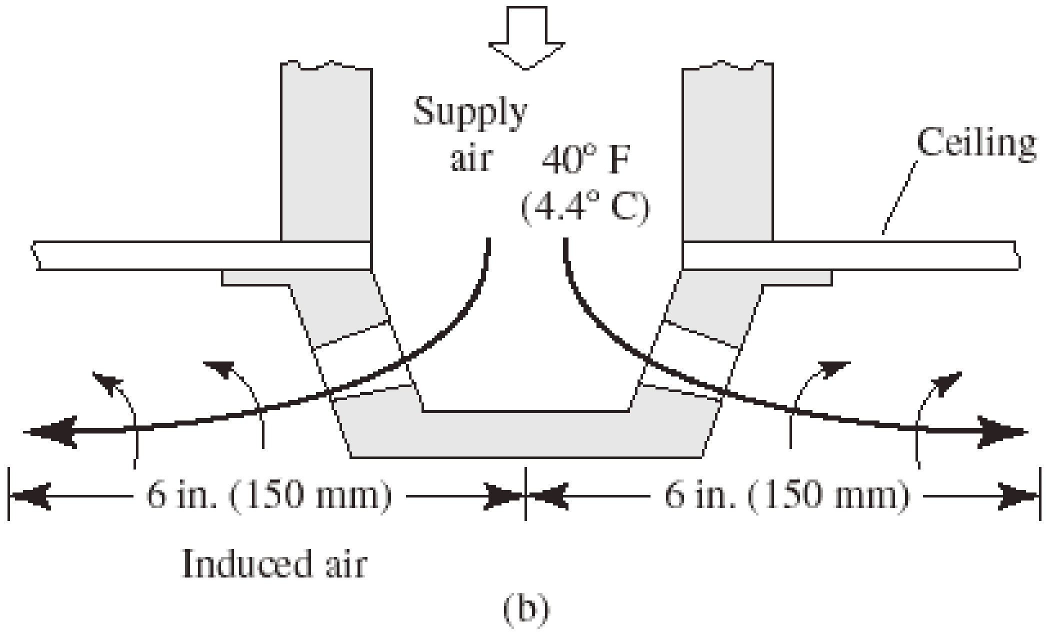




# Slot diffusers

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

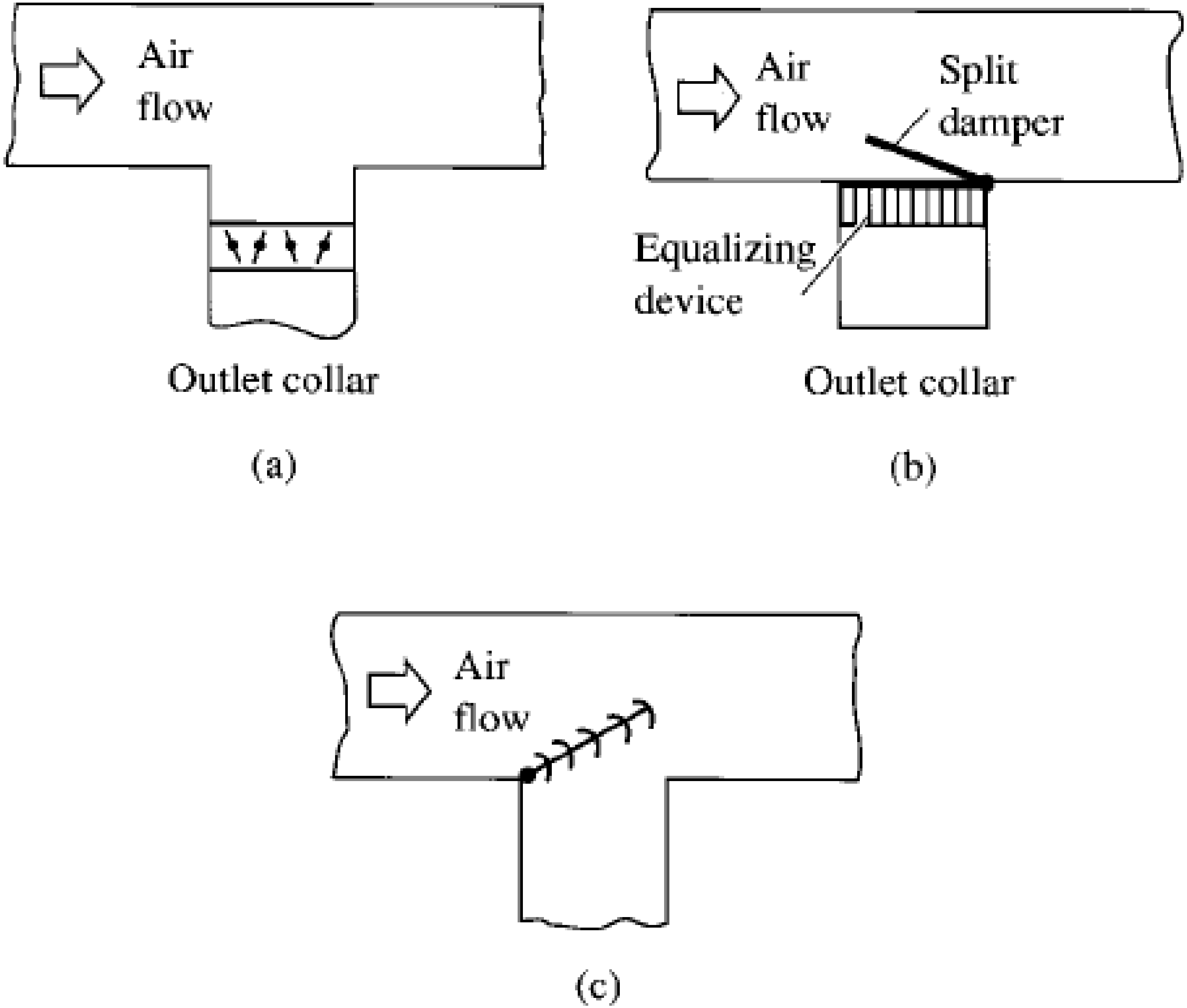



Round nozzle



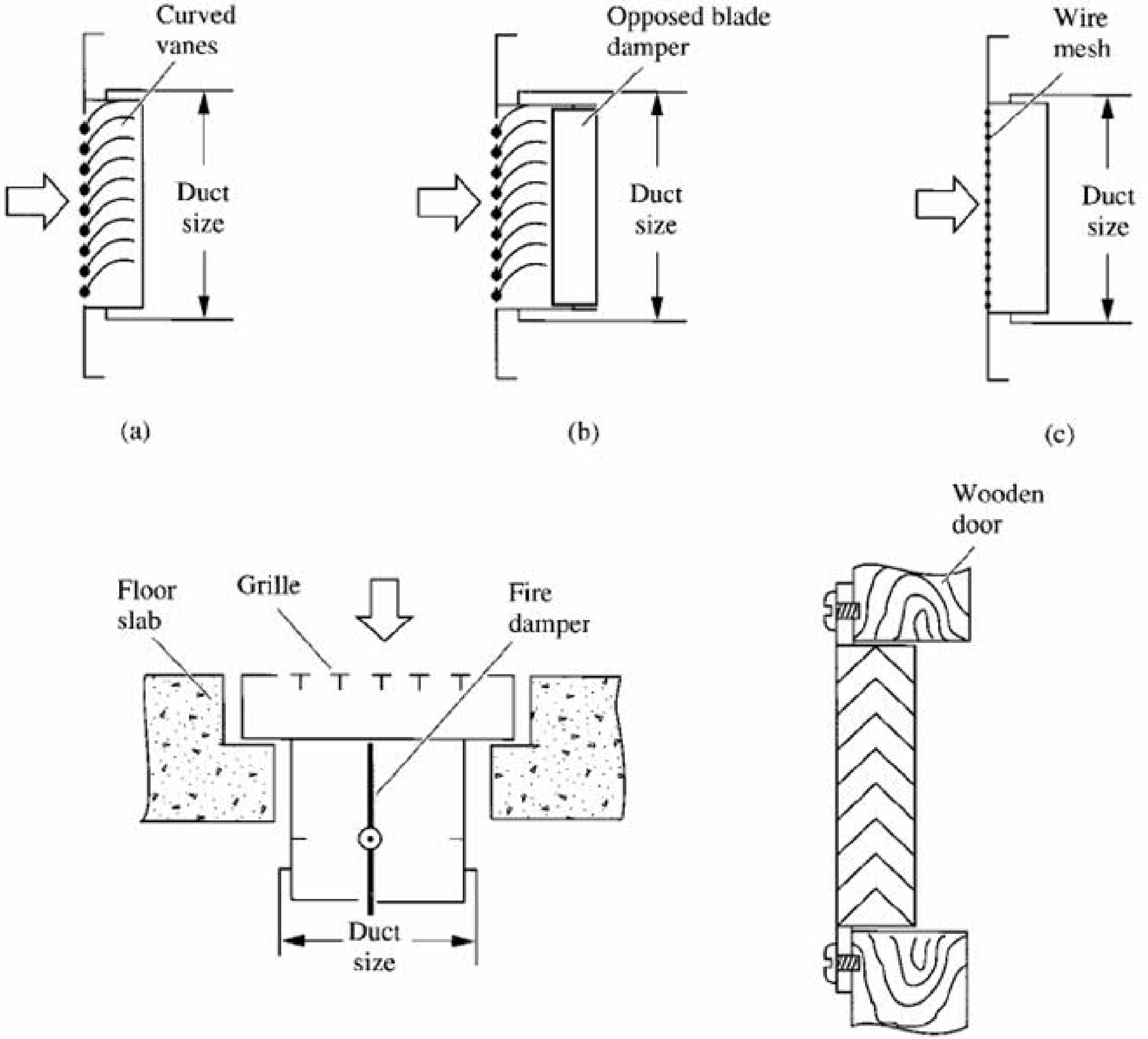

Nozzle diffuser

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



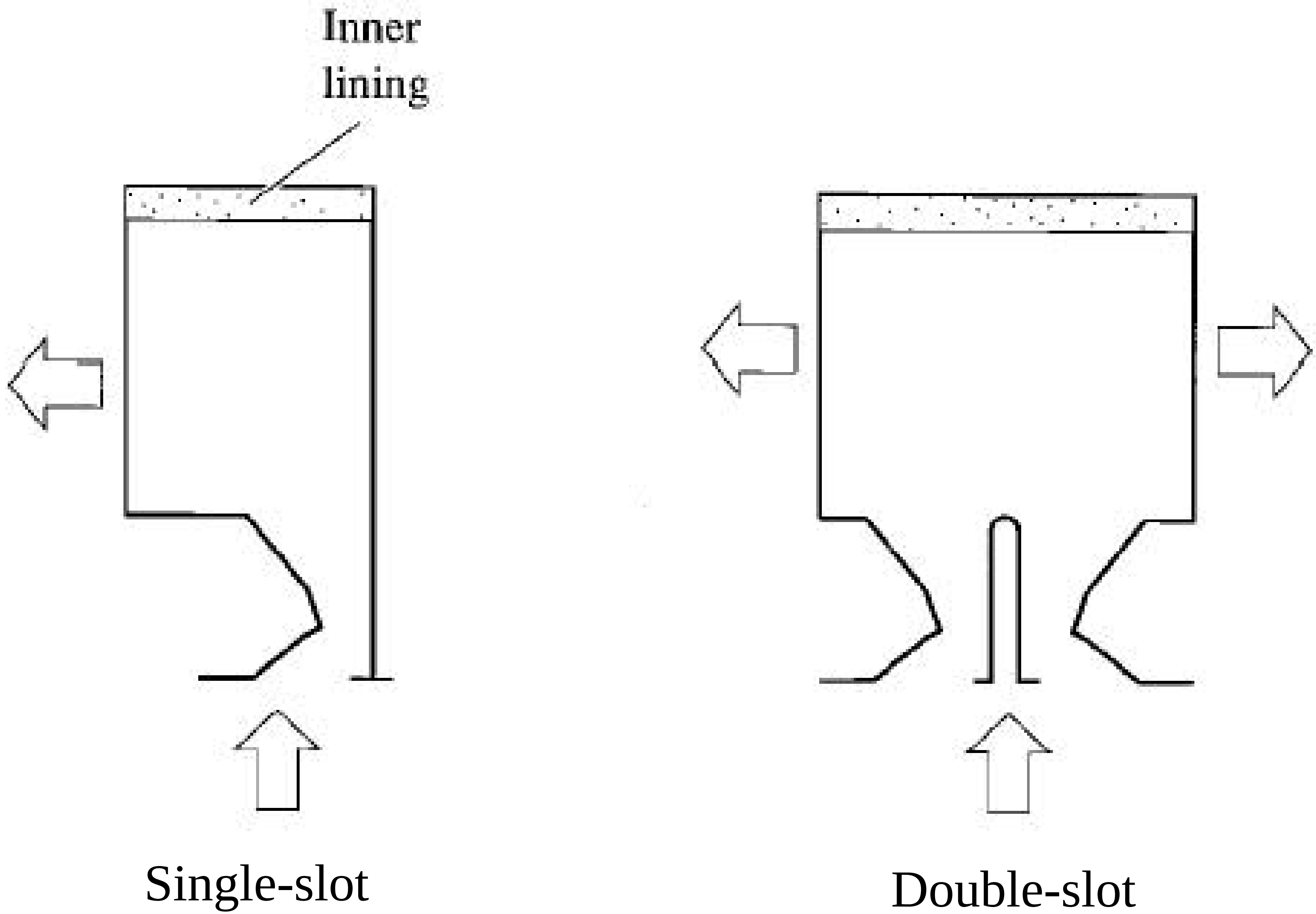

Accessories for supply outlets

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



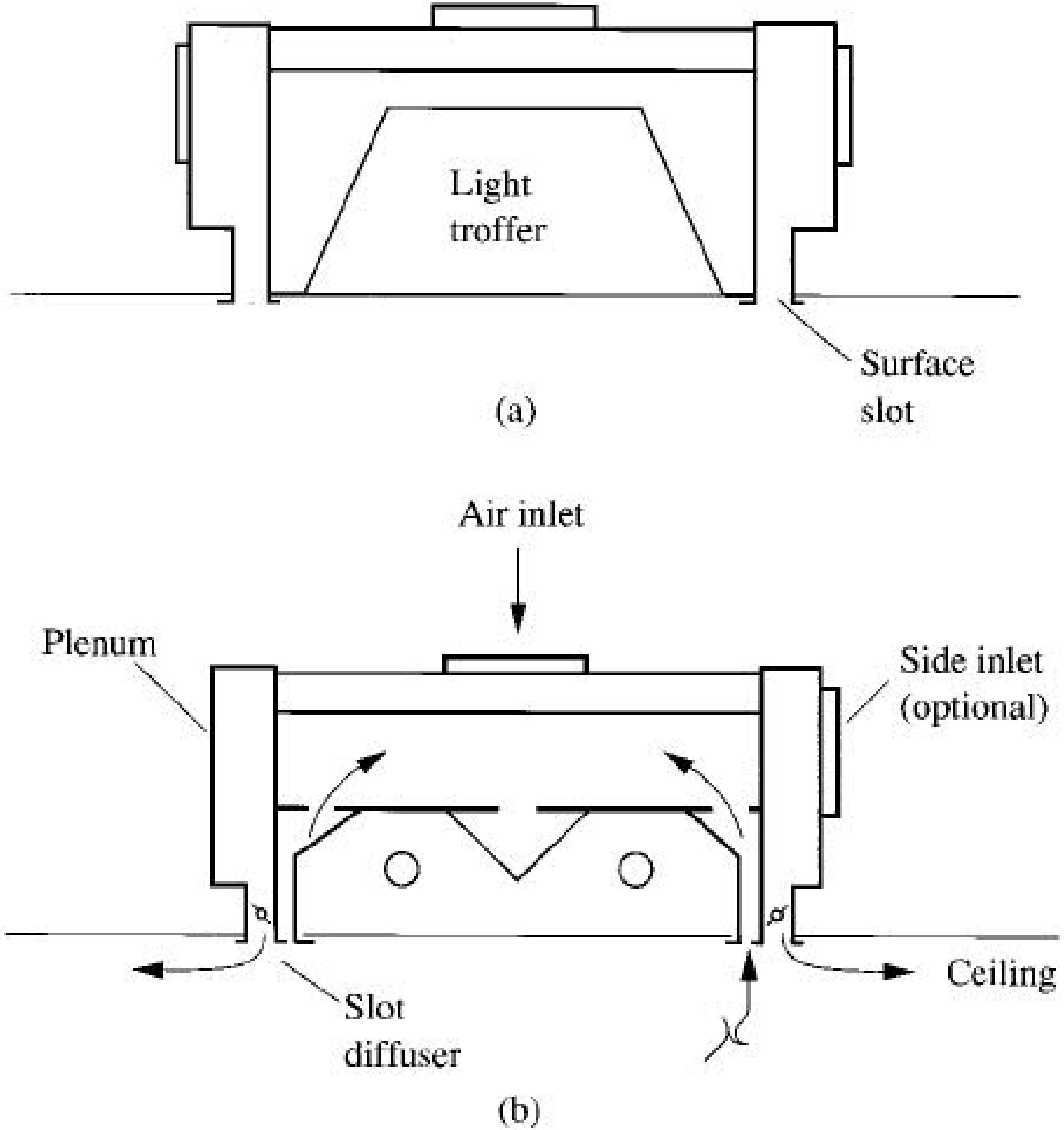

# Return grilles and registers

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




Return slots

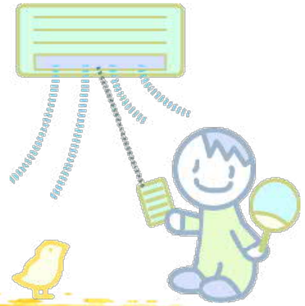
(Source: *Wang, S. K., 2001. Handbook of Air Conditioning and Refrigeration*)




Light troffer, slot diffuser and return slot combination

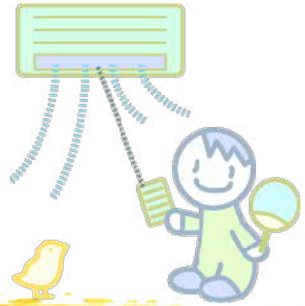
(Source: *Wang, S. K., 2001. Handbook of Air Conditioning and Refrigeration*)

# Mixing Flow



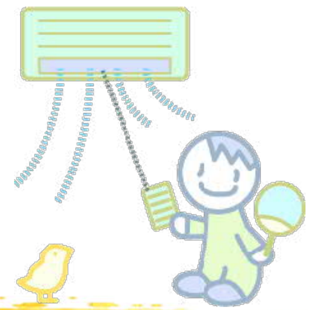
- Four typical airflow patterns
  - Mixing flow (most common)
  - Displacement flow
  - Projecting flow
  - Upward flow
- Also, task or personal air-conditioning systems

# Mixing Flow



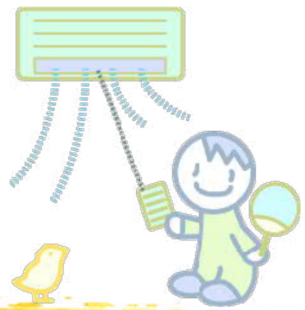
- Principles of mixing flow systems
  - Conditioned air discharged from outlets at high velocity
  - Conditioned air temperature may be above, below or equal to room air, depending on cooling/heating
  - Supply air mixed with room air by entrainment
  - Occupied zone is dominated by induced recirculating flow
  - Creates relatively uniform air velocity, temperature, humidity, and air quality

# Mixing Flow



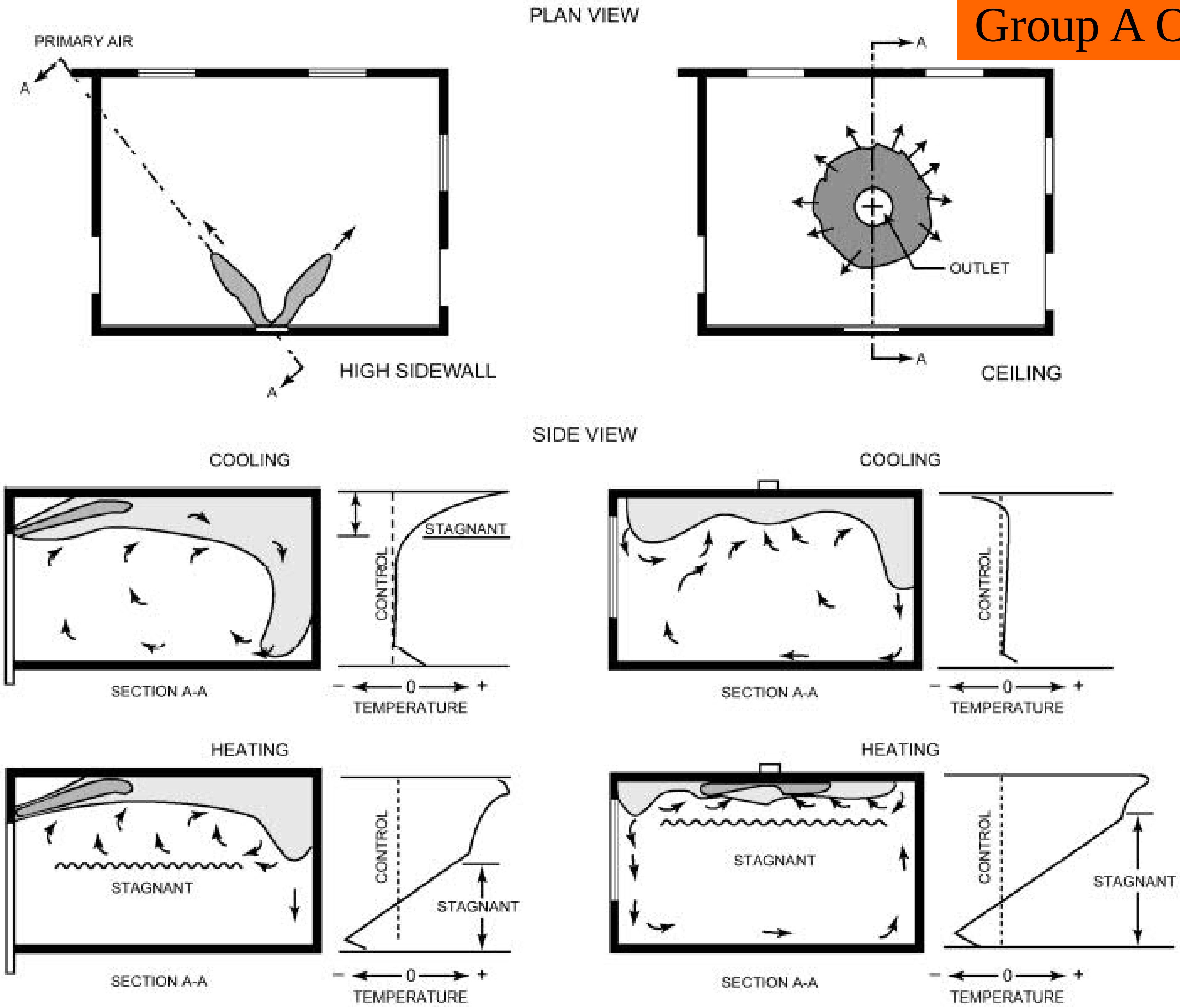
- Characteristics of mixing flow
  - Induction of space air into the air jet
  - Reverse airstream (induced) in occupied zone
  - Minimise the stagnant area in occupied zone
    - Air velocity of stagnant area < 0.1 m/s
  - Types & locations of return & exhaust inlets
    - Does not significantly affect airflow pattern
    - Does affect the thermal effectiveness factor $\varepsilon_T$

# Mixing Flow



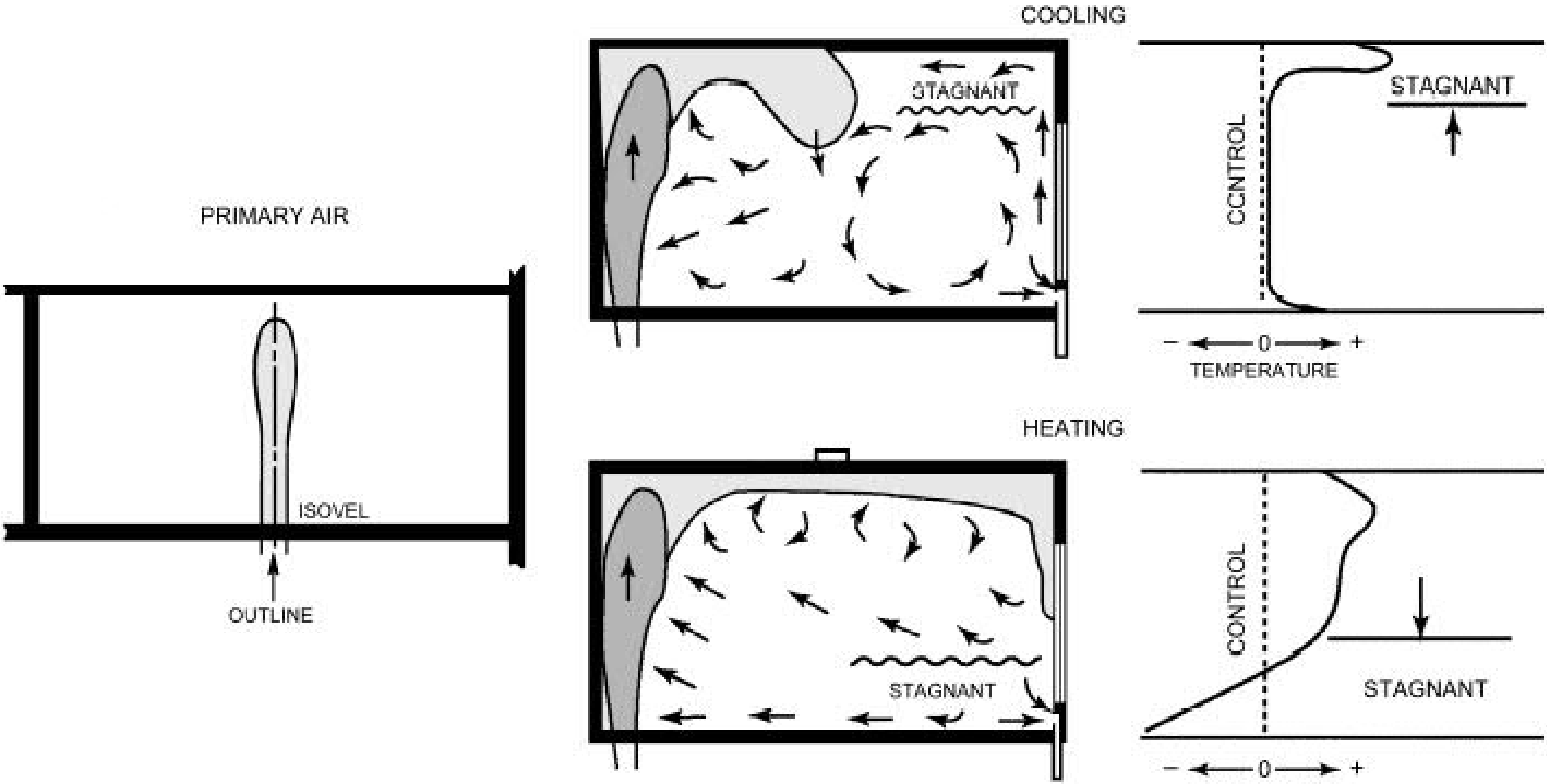
- Outlet classification (from ASHRAE)
  - Group A. mounted in or near ceiling that discharge air horizontally
  - Group B. mounted in or near floor that discharge air vertically in a non-spreading jet
  - Group C. mounted in or near floor that discharge air vertically in a spreading jet
  - Group D. mounted in or near floor that discharge air horizontally
  - Group E. mounted in or near ceiling that project primary air vertically

# Group A Outlets




(Source: *ASHRAE Handbook Fundamentals 2001*)

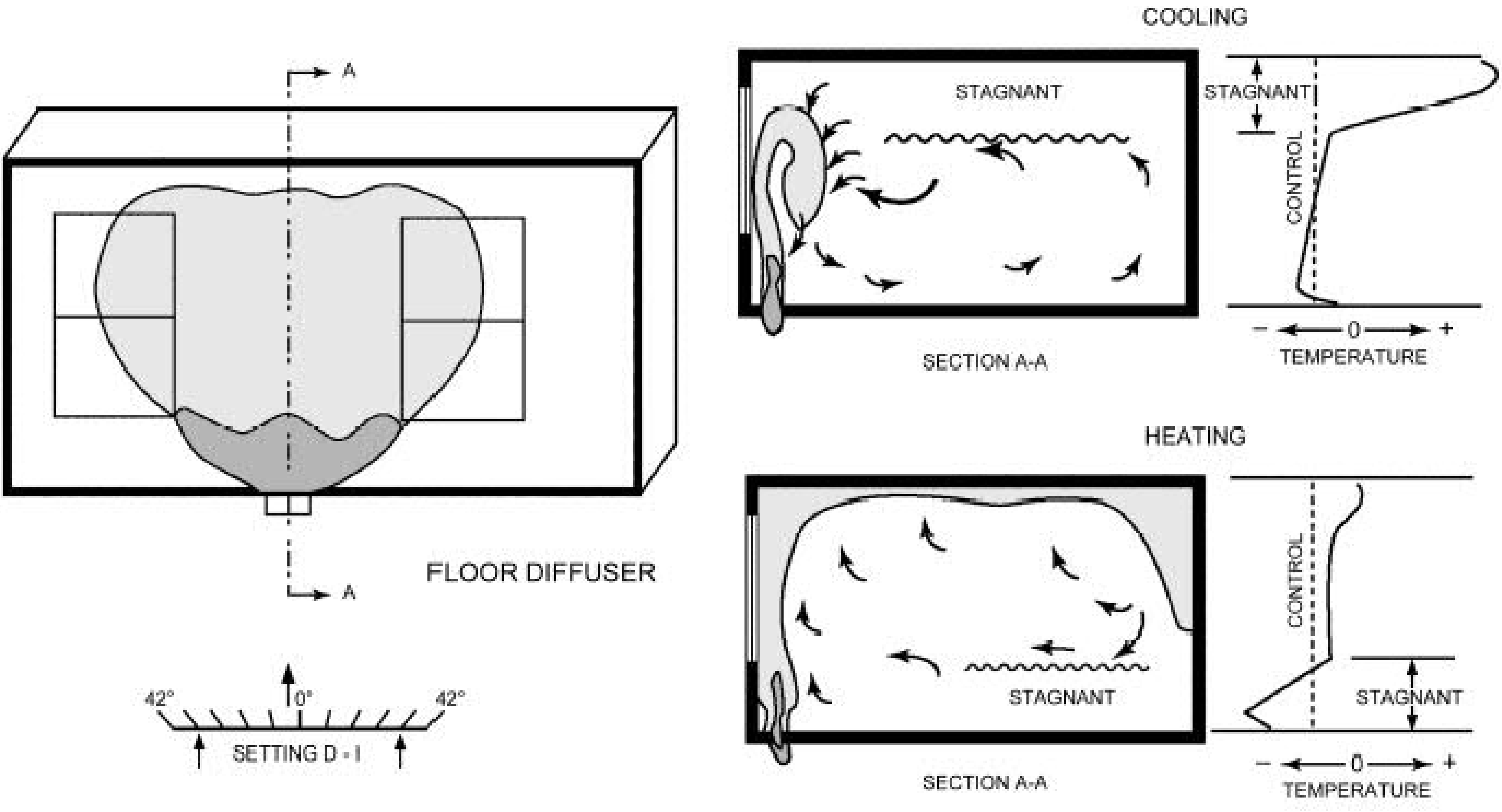
# Group B Outlets




OUTLET IN OR NEAR FLOOR, NONSPREADING VERTICAL JET

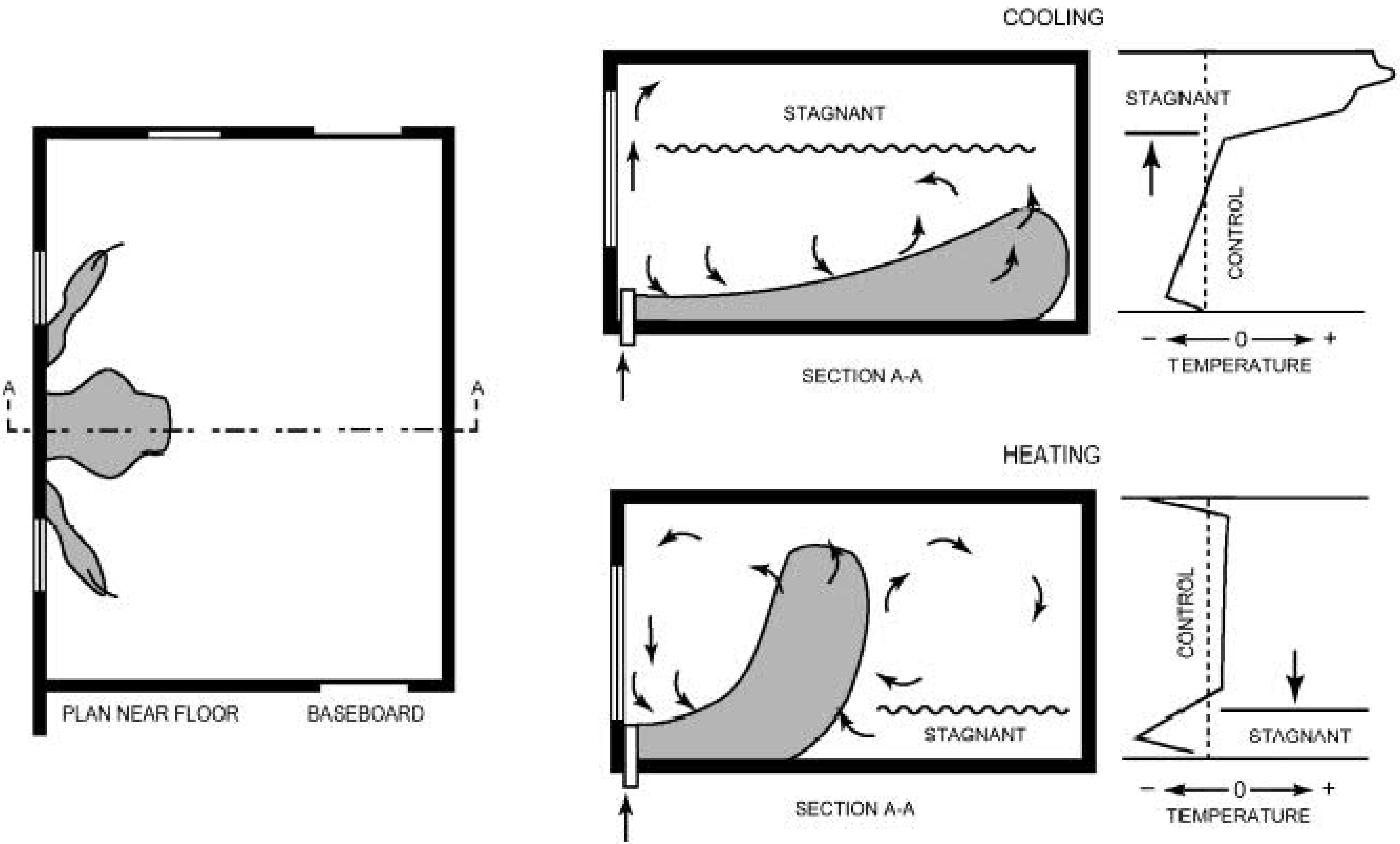
(Source: *ASHRAE Handbook Fundamentals 2001*)

# Group C Outlets



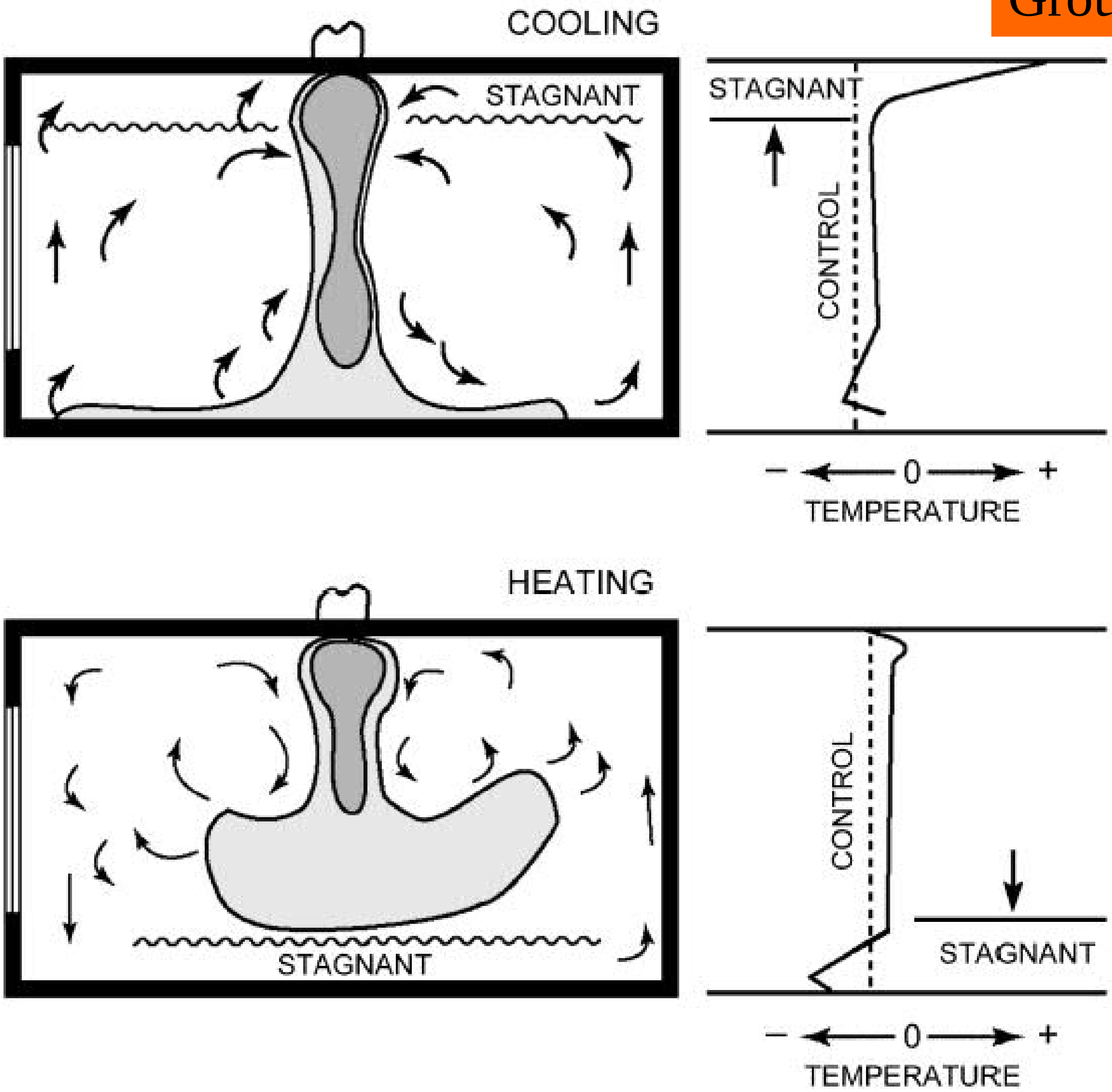

(Source: *ASHRAE Handbook Fundamentals 2001*)

# Group D Outlets



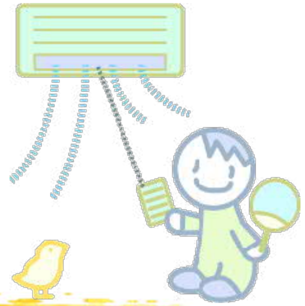

(Source: *ASHRAE Handbook Fundamentals 2001*)

# Group E Outlets



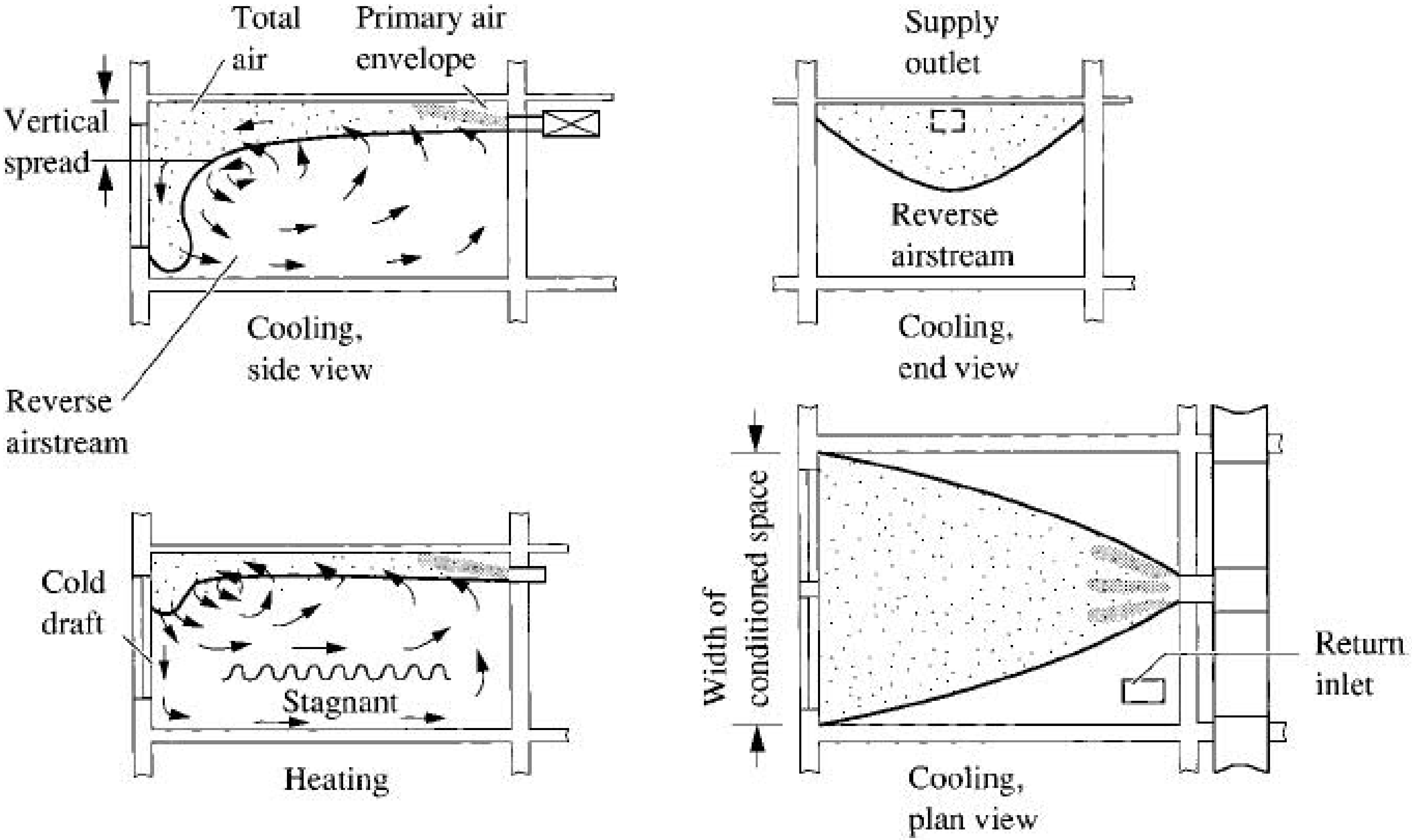

(Source: *ASHRAE Handbook Fundamentals 2001*)

# Mixing Flow



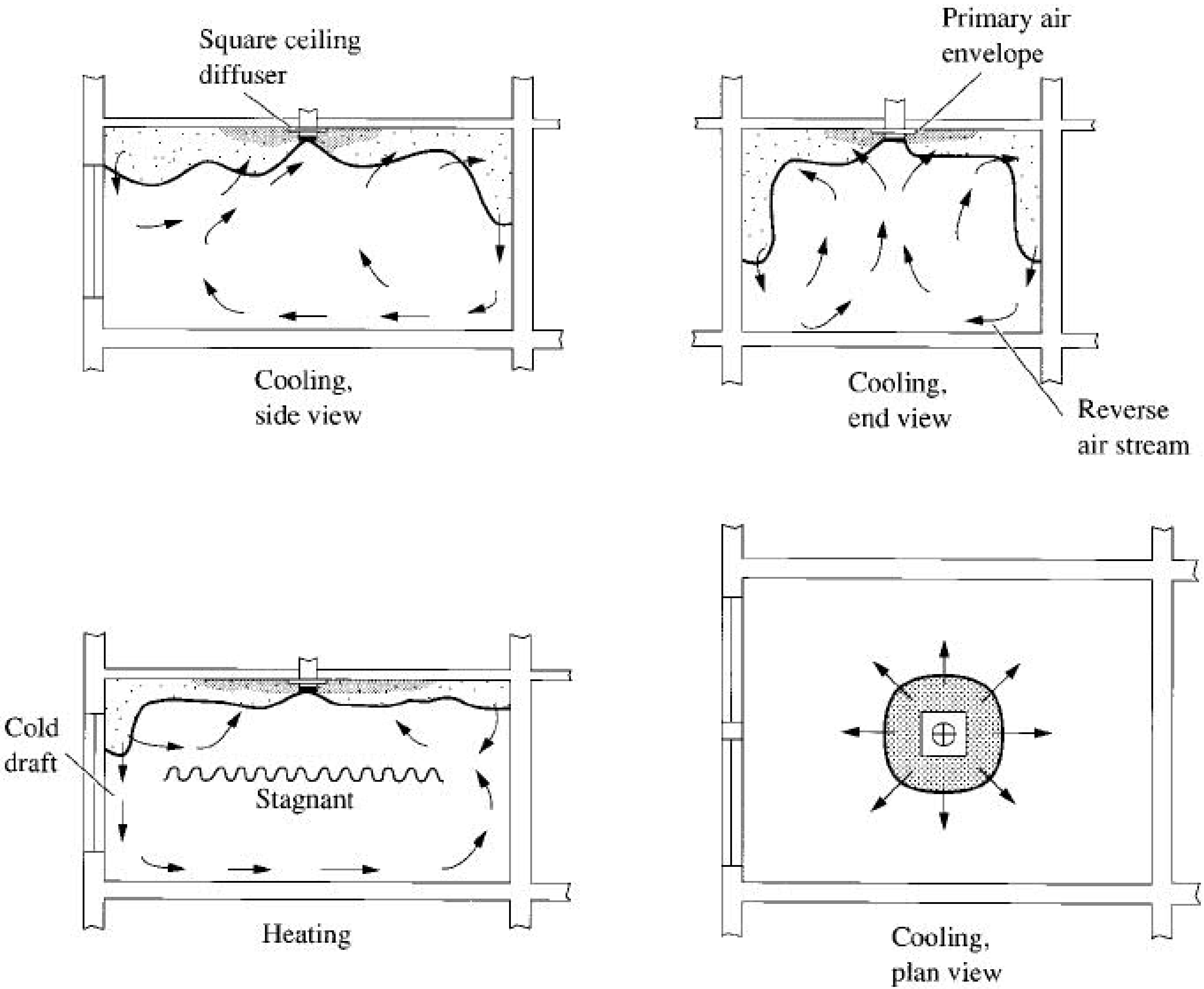
- Common types & locations of outlets
  - High side outlets
  - Ceiling diffusers
  - Slot diffusers
  - Sill and floor outlets
  - Outlets from stratified mixing flow
- Key questions
  - Will the air jet enter the occupied zone?
  - Will stagnant zone be formed?

Will the air jet enter the occupied zone?
Will stagnant zone be formed?



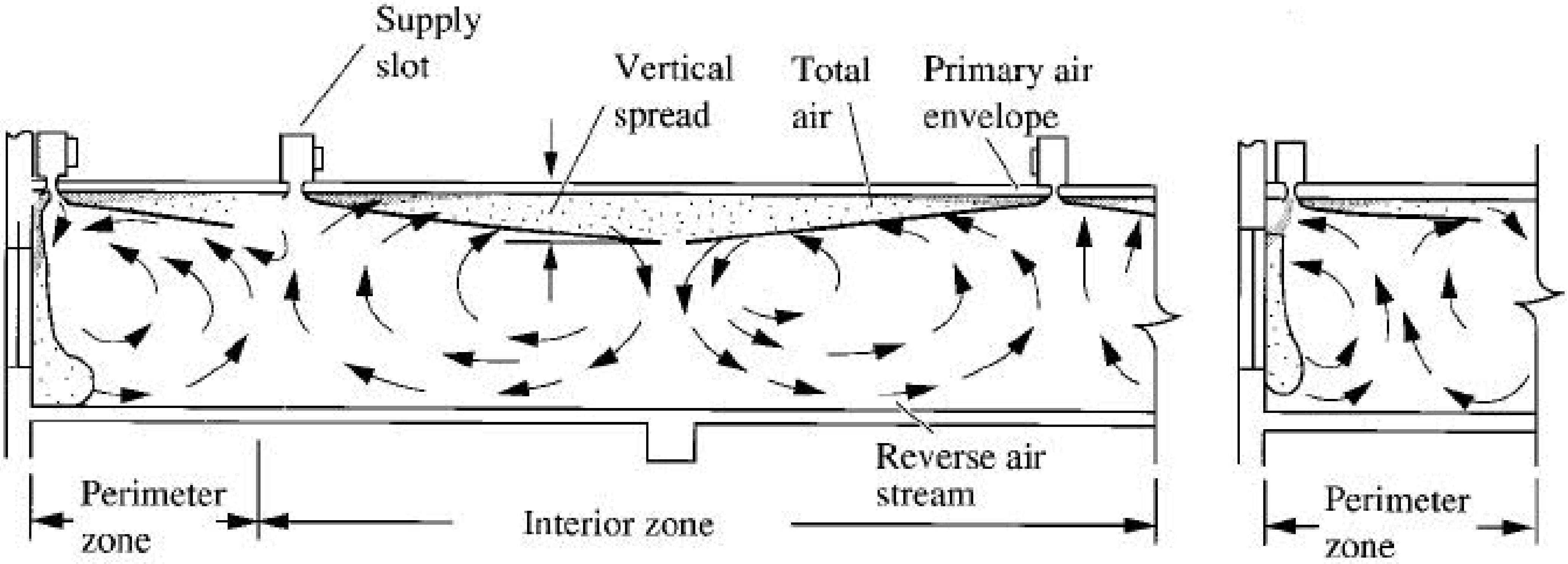

Mixing flow using high side outlets

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




# Mixing flow using ceiling diffusers

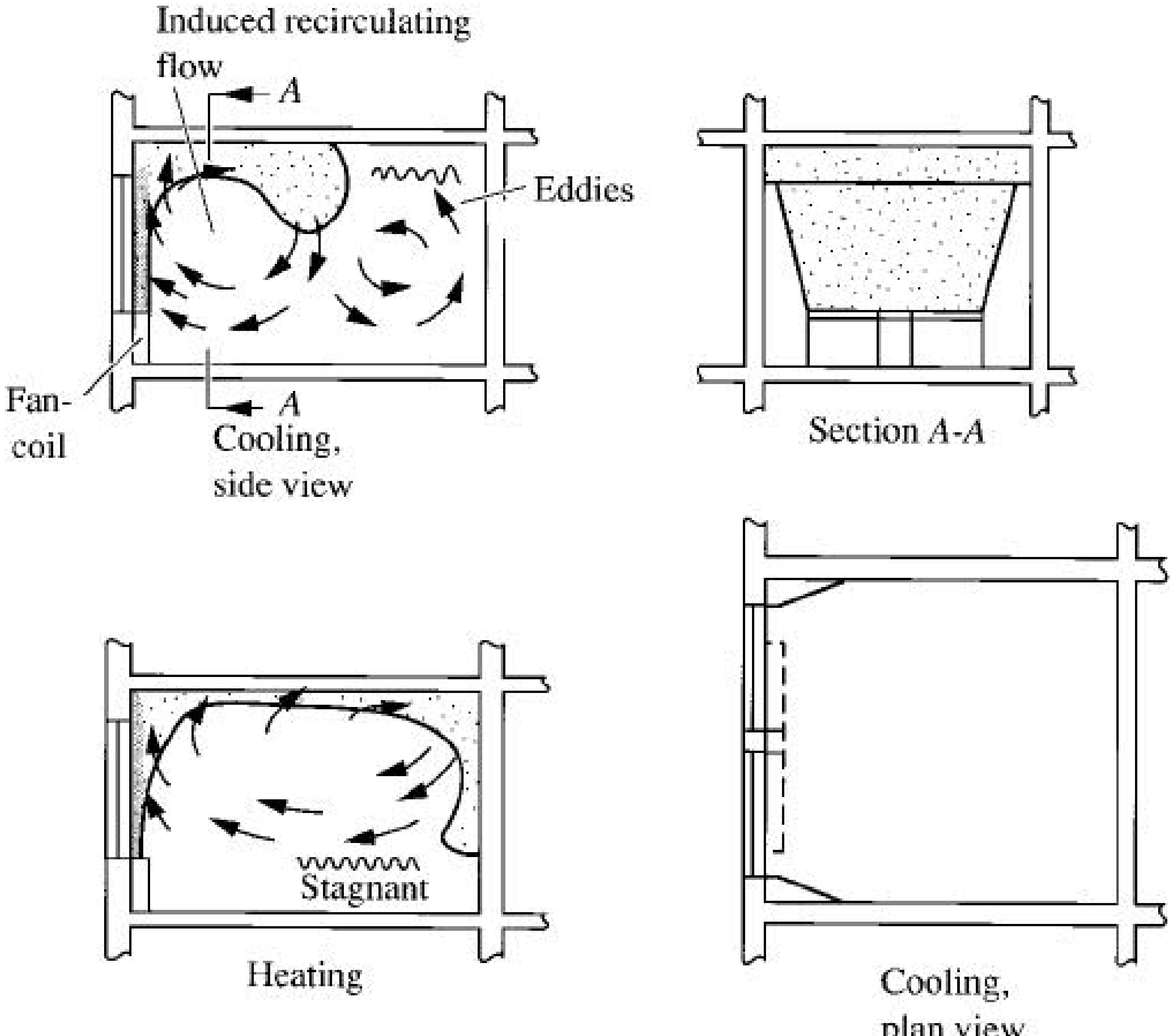
(Source: *Wang, S. K., 2001. Handbook of Air Conditioning and Refrigeration*)




(heating)

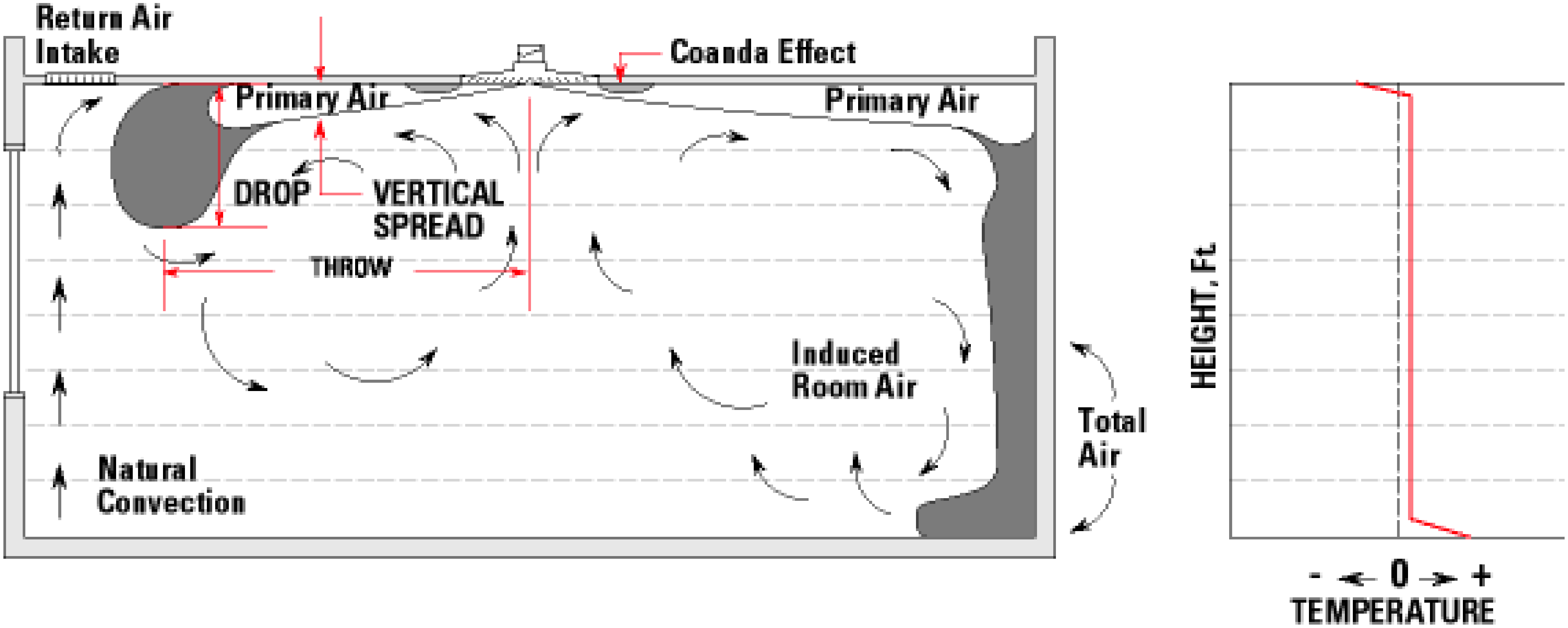
Mixing flow using slot diffusers

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



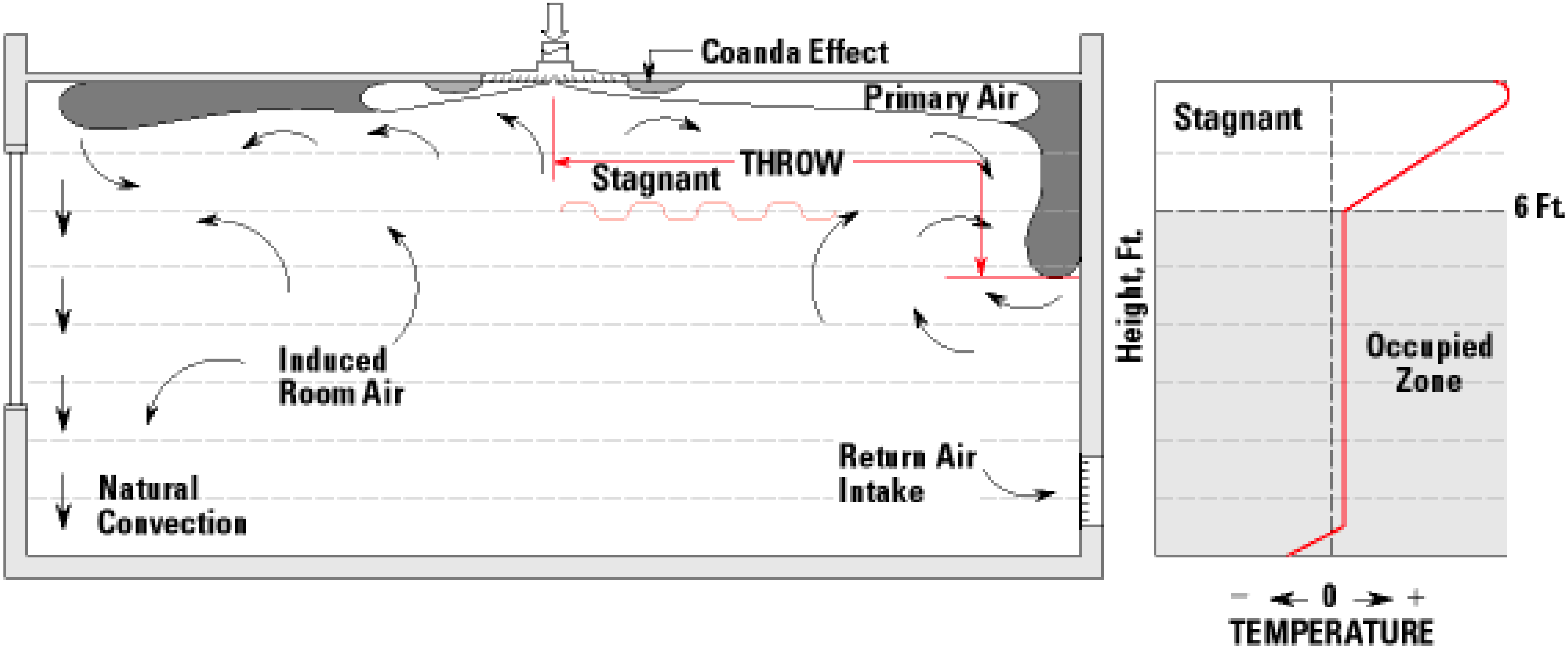

# Mixing flow using sill outlet

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



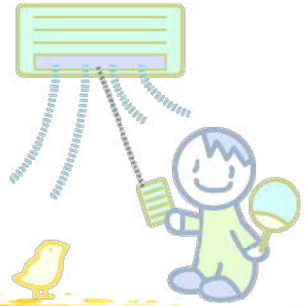

Space air diffusion with overhead cooling

(Source: http://www.price-hvac.com)




Space air diffusion with overhead heating

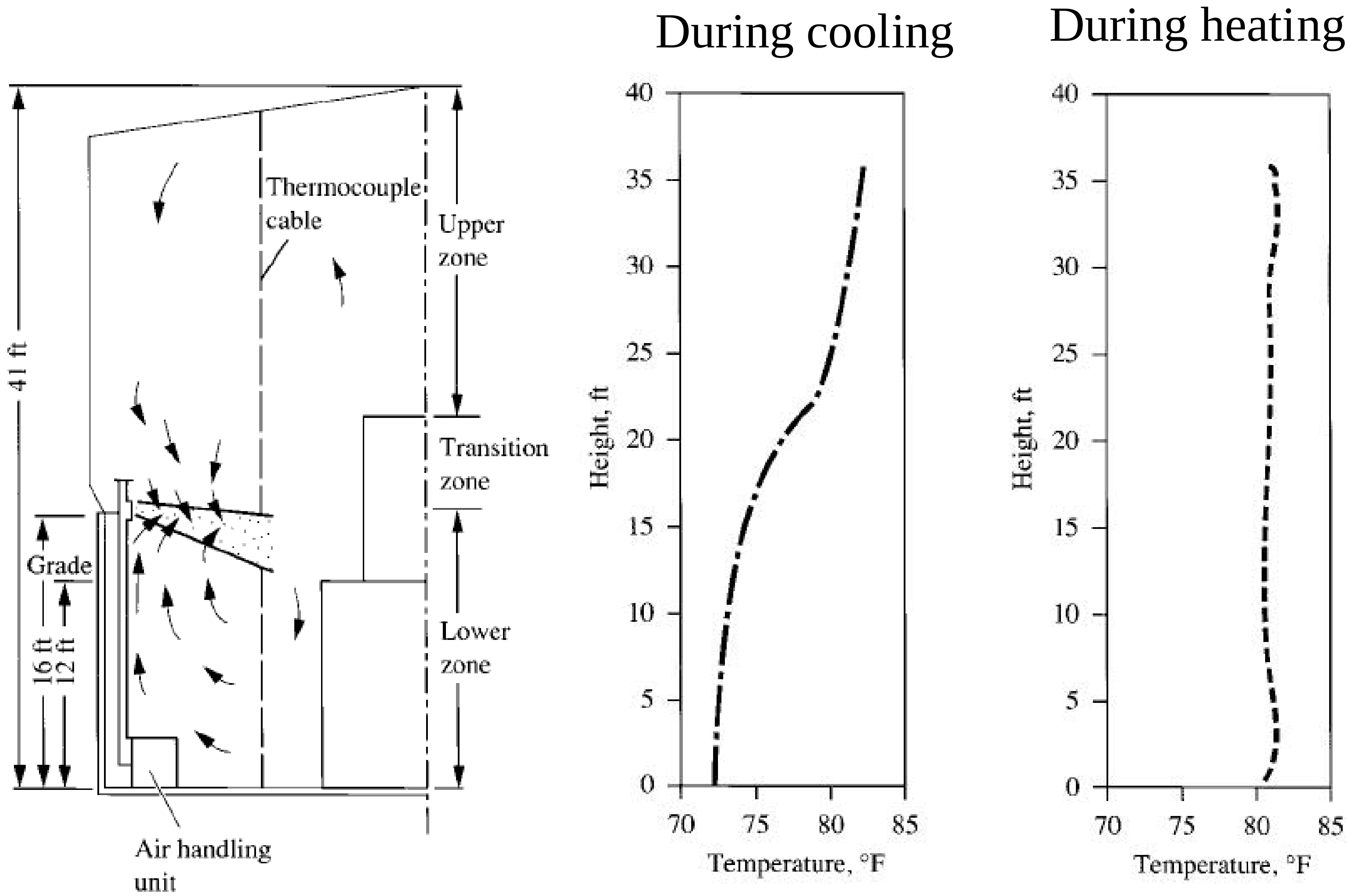
(Source: http://www.price-hvac.com)



# Mixing Flow

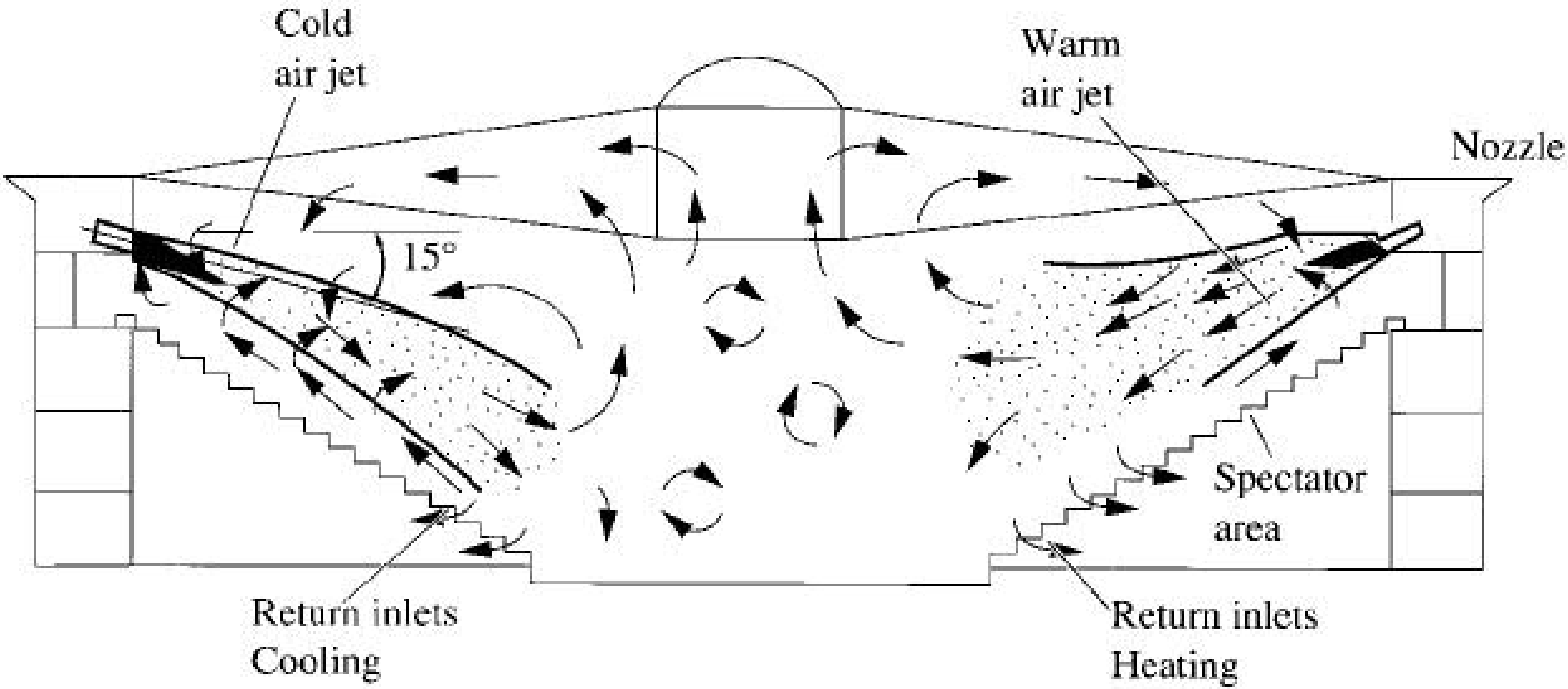
- In buildings with high ceiling*
  - More economical to stratify the air vertically into zones during cooling
  - Upper boundary of the lower zone is at the level of the supply outlet where air jet projects horizontally
  - Examples:
    - Stratified mixing flow in a nuclear plant
    - Large, high-ceiling indoor stadium (w/ supply nozzles)
    - Chek Lap Kok Airport

* See also Ventilation (and Air Conditioning) of Large Rooms
http://www.arca53.dsl.pipex.com/index_files/vent9.htm




Stratified mixing flow in a nuclear facility

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

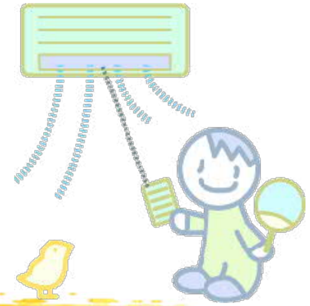



Stratified mixing flow in a large indoor stadium using supply nozzles

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

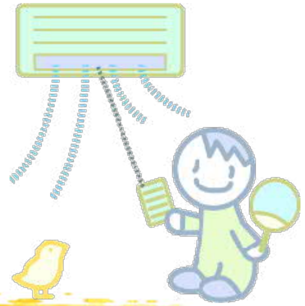

Hong Kong International Airport

# Mixing Flow



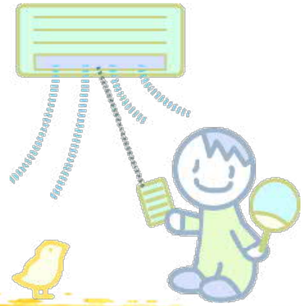
- Characteristics of stratified mixing flow
  - Convective heat transfer from hot roof is blocked
  - Cooling loads in lower zone is offset by supply air
  - Radiant heat from roof, wall & lights in upper zone enters the occupied zone and becomes cooling load
  - Although supply airflow rate & temp. affect the throw & drop of the air jet, the induced recirculating airflow patterns in upper & lower zones remain the same
  - Height of supply air jet determines upper boundary of the lower zone
  - Location of return inlets influences cooling load only when they are located in the upper zone

# Mixing Flow



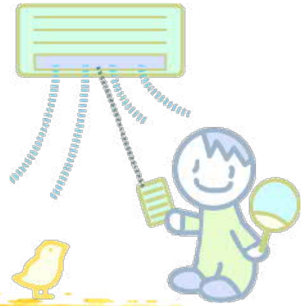
- Design & selection method
  - Review the form & use of the space, and determine if cooling or heating will be provided
  - Determine the amounts of airflow rates
  - Decide location for equipment
  - Obtain & review equipment catalogues (find acceptable styles & models of air terminals)
  - Lay out rough locations for air terminals
  - Select specific models & sizes

# Mixing Flow



- Design & selection method (cont'd)
  - Check performance criteria (patterns, throws, sound levels, pressure drops)
  - Relocate, reselect, recheck if needed
  - Select any terminal boxes, size & lay out branch ductwork
  - Prepare schedules, drawings & specifications
  - Coordinate with other consultants (e.g. architect, interior designer)

# Mixing Flow



- Select type of supply outlet
  - Requirements of indoor environmental control
    - Such as precise air movement & air temperature
  - Shape, size, and ceiling height of the building
  - Surface effect
  - Volume flow per unit floor area
    - Determine the number of outlets
  - Appearance
  - Cost

**Table 1 Guide to Use of Various Outlets**

| Type of Outlet | Air Loading of Floor Space, Max. L/s per $m^2$ | Approx. Max. Air Changes per Hour for 3 m Ceiling |
|---|---|---|
| Grille | 3 to 6 | 7 |
| Slot | 4 to 10 | 12 |
| Perforated panel | 5 to 15 | 18 |
| Ceiling diffuser | 5 to 30 | 30 |

[Source: *ASHRAE Handbook HVAC Systems & Equipment 2000*, Chapter 17]

**Table 4 Air Diffusion Performance Index (ADPI) Selection Guide**

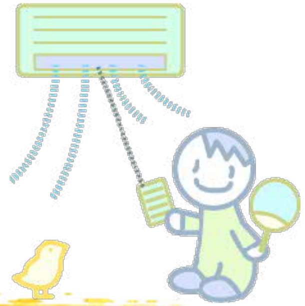
| Terminal Device | Room Load, W/m² | $T_{0.25}/L$ for Maximum ADPI | Maximum ADPI | For ADPI Greater than | Range of $T_{0.25}/L$ |
|---|---|---|---|---|---|
| High sidewall grilles | 250 | 1.8 | 68 | — | — |
| | 190 | 1.8 | 72 | 70 | 1.5–2.2 |
| | 125 | 1.6 | 78 | 70 | 1.2–2.3 |
| | 65 | 1.5 | 85 | 80 | 1.0–1.9 |
| Circular ceiling diffusers | 250 | 0.8 | 76 | 70 | 0.7–1.3 |
| | 190 | 0.8 | 83 | 80 | 0.7–1.2 |
| | 125 | 0.8 | 88 | 80 | 0.5–1.5 |
| | 65 | 0.8 | 93 | 90 | 0.7–1.3 |
| Sill grille, straight vanes | 250 | 1.7 | 61 | 60 | 1.5–1.7 |
| | 190 | 1.7 | 72 | 70 | 1.4–1.7 |
| | 125 | 1.3 | 86 | 80 | 1.2–1.8 |
| | 65 | 0.9 | 95 | 90 | 0.8–1.3 |
| Sill grille, spread vanes | 250 | 0.7 | 94 | 90 | 0.6–1.5 |
| | 190 | 0.7 | 94 | 80 | 0.6–1.7 |
| | 125 | 0.7 | 94 | — | — |
| | 65 | 0.7 | 94 | — | — |
| Ceiling slot diffusers (for $T_{100}/L$) | 250 | 0.3 | 85 | 80 | 0.3–0.7 |
| | 190 | 0.3 | 88 | 80 | 0.3–0.8 |
| | 125 | 0.3 | 91 | 80 | 0.3–1.1 |
| | 65 | 0.3 | 92 | 80 | 0.3–1.5 |
| Light troffer diffusers | 190 | 2.5 | 86 | 80 | <3.8 |
| | 125 | 1.0 | 92 | 90 | <3.0 |
| | 65 | 1.0 | 95 | 90 | <4.5 |
| Perforated, louvered ceiling diffusers | 35–160 | 2.0 | 96 | 90 | 1.4–2.7 |
| | | | | 80 | 1.0–3.4 |

[Source: *ASHRAE Handbook Fundamentals 2001*, Chapter 32]

# Mixing Flow

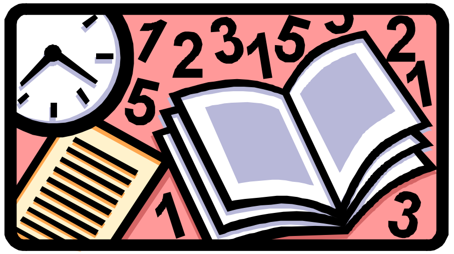
- Select & check the specific supply outlet
  - Major parameters
    - Sound level
      - Combined sound level shall be at least 3 dB lower than the recommended NC criteria
      - Typical air veolcities: 2.5 to 6.25 m/s
    - Drop of cold air jet
      - Will cold air jet enter the occupied zone?
    - Total pressure loss
      - Typically, total pressure loss shall be lower than 50 Pa

# Mixing Flow



- Determination of the final layout is often an iteration process
- Some good practices for return inlets:
  - If a ceiling plenum is used as return plenum, return inlets shall be located outside supply air jet, above return airstream, or near a concentrated heat source
  - Recommended face velocities for return inlets:
    - Above occupied zone: 4 to 5 m/s
    - Within occupied zone: 2 to 3 m/s
    - Door louvres: 1.5 to 2.5 m/s

# Further Reading




- Price HVAC: Training Modules [http://www.priceindustries.com/resources/type/videos/training-modules]
  - Basics of HVAC (10:57)
  - Comfort Criteria (9:58)
  - Space Air Diffusion (8:35)
  - Air Outlet Selection (28:08)
  - Displacement Ventilation (33:15)
  - Underfloor Air Distribution (39:55)