Space Air Diffusion II

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Cold Air Distribution

- Lower supply air temp. = 4.4 to 7.2 °C
- Conventional air distribution = 12.7 to 15.0 °C
- Applied mainly in conjunction with ice storage systems
  - Lower chw temp. (1.1 to 2.2 °C) (from ice storage)
- Main advantages:
  - Reduce design supply volume flow (larger ΔT)
  - Air-side components can be downsized
  - Fan energy use can be reduced
  - Reduced fan sound levels
- Drawbacks: dumping of cold air jet & IAQ issues
Cold Air Distribution

• Design considerations
  • Condensation
    • Cooled surfaces shall be well insulated & sealed
  • Comfort
    • Air supplied at lower velocities: diffuser performance is affected (e.g. dumping & stagnant at low load)
  • Indoor air quality
    • Minimum ventilation flow is required; may need reheat
  • Controls
    • Start-up & shut-down, humidity controls, VAV, etc.
Cold Air Distribution

- Two methods for cold air space diffusion
  - High induction nozzle diffusers
    - Direct from AHU or package unit
  - Fan-powered VAV boxes
    - Mix low-temperature supply air with return air before supplied to the conditioned space

- Characteristics of cold air distribution
  - Higher $\sqrt{A_r / D_o}$ value
  - Higher supply air velocity & jet turbulence
  - Good surface effect (adequate throw, small drop)
  - ADPI $\geq$ 80 at both design & reduced airflow
Series flow fan power terminal

Cold Supply Air

Warm Plenum Air

Uniform Discharge Air Temperature

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

• Design checks
  • Performance of ceiling & slot diffusers
    • Any difference compared with conventional system?
  • Fan-powered VAV boxes
    • In parallel or in series
    • Mixing w/ return air to get suitable supply temp.
    • Provide space air movement
    • Higher noise & more maintenance
  • Surface condensation
    • Sufficient thermal insulation is needed to prevent this
Displacement Flow

• Displacement flow
  • Cold supply air at a velocity nearly equal to the required velocity and displace the original air with piston-like airflow w/o mixing
  • If properly designed, it can give:
    • Better IAQ in occupied zone
    • Higher space diffusion effectiveness
    • Low turbulence intensities & fewer draft problems
  • Drawbacks:
    • Require greater supply volume flow rate
    • Higher construction cost
Displacement ventilation (DV)  
Mixing ventilation (MV)
Typical displacement ventilation room layout
Displacement flow characteristics
(Source: http://www.price-hvac.com)
Displacement ventilation system
Displacement Flow

• Airflow patterns
  • Because of low discharge velocity, air motion is influenced to a large degree by convection flows
    • Convection flows (or thermal plumes) are created by heat sources, e.g. people, equipment, warm windows
    • Cold sinks (e.g. cold windows) may create flows down

• Airflow penetration
  • Supply air spread across the floor in a thin layer, filling the entire space
  • Flow around & beyond obstructions
Displacement flow patterns
(Source: http://www.price-hvac.com)
Figure 7 - Obstruction

Figure 8 - Irregular Room Geometry

Airflow penetration
(Source: http://www.price-hvac.com)
Displacement Flow

- Diffuser airflow patterns
  - To avoid draft, displacement diffuser shall deliver the supply air uniformly at low velocity
    - With internal equalization baffle & low free area face
  - For cool air supply, it will falls towards the floor
  - For isothermal air, it will distribute horizontally
  - For heated air, the discharge air will rise
    - Therefore, it is not recommended to supply heated air
Displacement diffuser airflow pattern
(Source: http://www.price-hvac.com)
Displacement Flow

- Contaminant distribution
  - Can reduce contaminant in lower portion of room
  - Actual distribution is influenced by factors e.g. contaminant source type & location, human body convection and space height, strength of thermal plume

- Ventilation effectiveness
  - Displacement can achieve around 1.2-1.4; most mixing systems is around 1.0
Figure 12 - Contaminant Distribution

Ref: REHVA Guidebook

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

- Temperature distribution
  - Temperature gradient between the floor & ceiling
  - Also known as “Stratification”
  - Affected by factors e.g. supply air volume, room cooling load, location & type of heat source, height of the space
- Controlling stratification is critical to maintain thermal comfort
- If heating is needed, may use radiator to offset cold downdrafts near the windows
Displacement ventilation – temperature gradient

(Source: http://www.price-hvac.com)
Displacement ventilation – temperature gradient

(Source: http://www.price-hvac.com)
Displacement ventilation and radiator
(Source: http://www.price-hvac.com)
Displacement Flow

- Stratified displacement flow
  - First introduced in Scandinavian countries
  - Low-level supply outlet
  - Above heat & contaminated sources
    - Heated air rises upward due to buoyancy effect
    - Supply air is entrained into the upward convective flow
    - Stationary level: upward flow = supply flow
    - Two-zone stratified model: upper zone & lower zone
Stratified displacement flow in a typical room
Displacement Flow

- Characteristics of stratified displacement flow
  - Cold air supply of usually 100% outdoor air
  - Air must be supplied at low velocity (< 0.3 m/s) & at a height less than 0.54 m above floor
  - Cold air supplied at 2.8 to 5 °C lower than occupied zone
  - Height of lower zone shall be higher than a seated occupant (1.4 m); all air is supply air in lower zone
  - Smaller cooling load density (max. 41 W/m²)
  - Return or exhaust inlets located near ceiling level
Displacement Flow

- Design procedure
  - Step 1: determine summer cooling load
    - Occupants, lights, equipment, envelope
  - Step 2: determine cooling load ventilation flow rate
    - Equation from the ASHRAE design guide
  - Step 3: determine flow rate of fresh air
  - Step 4: determine supply air flow rate
    - Max \{Step 2, Step 3\} flow rates
  - Step 5: determine supply air temperature
  - Step 6: determine exhaust air temperature
Displacement Flow

- Common diffuser types
  - Rectangular units
  - Corner units
  - Semi-circular units
  - Circular units
  - Floor mounted units
Underfloor Air Distribution

• Upward flow underfloor air distribution
  • Conditioned air from floor plenum (0.3-0.45 m)
    • Usually ductless (air duct has also been used in the past)
  • Supply outlets
    • Floor diffusers, fan-driven units, desktop units, supply outlets from fan coil units and water-source heat pumps
    • Often partial displacement & partial mixing
• Cool primary air from AHU
• Applications of underfloor air distribution
  • Computer rooms air conditioning
  • Commercial buildings (w/ access raised floor systems)
Upward flow underfloor air distribution system
Underfloor air supply

(Source: http://www.price-hvac.com)
Underfloor air distribution system

(Source: ASHRAE Underfloor Air Distribution Design Guide)
Office space with underfloor air distribution & task air-conditioning

(Source: ASHRAE Underfloor Air Distribution Design Guide)
Installation of raised floor system in open plan office
(Source: ASHRAE Underfloor Air Distribution Design Guide)
Underfloor Air Distribution

• Design factors of underfloor air distribution
  • Thermal storage of floor plenum
    • Primary air in direct contact with concrete floor slab
  • Heat unneutralised
    • Upward air flow lifts the heat unneutralised to ceiling
    • Greater capability to capture/exhaust heat thru’ ceiling
  • Maintaining a consistent access plenum temp.
    • Blending air for suitable temperature; travel distance
  • Master zone air temp. control
    • Important for VAV system to response to load changes
Underfloor Air Distribution

• Advantages of underfloor air distribution
  • Integrated well with raised floor plenum
  • Can be very flexible for future changes/relocations
  • Conditioned air is supplied directly to occupants
  • Stagnant air can be reduced (if ceiling return)
  • Upward flow lifts some unneutralised heat
  • It can utilise thermal mass of access floor & slab to reduce peak demands

• Disadvantages
  • Higher initial costs
  • Need for raised floor system & floor diffusers
Overhead VAV Distribution

- floor slab
- ceiling plenum
- Coanda effect for mixing
- 55°F (13°C)
- uniform space temperature, 75°F (24°C)
- wiring access

Displacement Ventilation

- floor slab
- VAV terminal
- 85°F (29°C)
- Requires high ceiling to limit “nose-to-toes” stratification to 5°F (3°C)
- 77°F (25°C)
- stratification layer
- 73°F (23°C)
- 65°F (18°C)
- typically 12 ft (3.6 m) or more
“Partial” Displacement Ventilation (Underfloor Air Distribution)

- Floor slab
- Ceiling plenum
- 82°F (28°C)
- Stratification layer
- Uniformly 75°F (24°C)
- 65°F (18°C)
- Diffuser

12 ft (3.6 m) or less

(Source: UC Berkeley)
Comparison of typical vertical temperature profiles

(Source: ASHRAE Underfloor Air Distribution Design Guide)
References

• ASHRAE design guides:
  • ASHRAE, 2013. *UFAD Guide: Design Construction and Operation of Underfloor Air Distribution Systems*

• Suppliers information:
  • [http://www.priceindustries.com](http://www.priceindustries.com)
  • [http://www.flexiblespace.com](http://www.flexiblespace.com)
Unidirectional Flow

- Unidirectional flow
  - Airstream flows in the same direction as uniform airflow showers the entire working area or occupied zone (known as “laminar flow”)
- Examples:
  - Clean rooms (downward or horizontal flow)
  - Ventilating or perforated ceiling
- Advantages:
  - Contaminants generated cannot move laterally
  - Dust particles will not be carried to higher levels
Unidirectional flow for clean rooms

Ventilating ceiling

Ventilating ceiling: an example for kitchen

(Source: http://www.reven.de)
Unidirectional Flow

• Ceiling plenum & supply air velocity
  • To create a more uniform supply air velocity, the max. air velocity inside the ventilating ceiling plenum shall be low
  • If sufficient plenum height & few obstructions, distributing ductwork inside is not needed

• Applications of ventilating ceiling
  • Industrial process
  • Indoor sports stadium for badminton (＜0.2 m/s)
Unidirectional Flow

- Hospital applications (more critical)
  - Main purpose: control of airborne contaminants
  - Such as operating theatre and isolation wards
- Operating theatre
  - Large fresh air ventilation (100% outdoor air)
  - Large volume of supply air
  - At low uniform velocity to promote stable downward flow of air
Flow patterns in hospital operating theatre

Laminar flow - full ceiling supply

Laminar flow - partial ceiling supply

(Source: http://www.price-hvac.com)
Hospital operating theatre (laminar flow with air curtains)

(Source: http://www.price-hvac.com)
Hospital operating theatre (typical design)
(Source: http://www.price-hvac.com)
Hospital operating theatre (typical design)

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

- Hospital applications - isolation wards
  - Infectious isolation rooms
    - Patients with infectious diseases
    - Kept at a **negative pressure**
  - Protective isolation rooms
    - Patients with a high susceptibility to infection
    - Kept at a **positive pressure**
  - HEPA filters will be used
  - Ante rooms are recommended to minimize exchange of air between a hallway and the isolation room
  - Airflow pattern: protect health care staff or patient
Diagram #1 - Infectious Isolation Room

Infectious isolation room

(Source: http://www.price-hvac.com)
Diagram #2 - Protective Isolation Room

Protecive isolation room

(Source: http://www.price-hvac.com)
SARS test chamber (inside HKU BSE Lab)
Projecting Flow

- Cold or warm air jet projected to target zone
- Benefits of projecting flow
  - Better control of temp., air cleanliness & air movement in a localised environment
  - Spot cooling improve occupants’ thermal conditions & reduce heat stress
  - Greater direct outdoor air supply
  - Direct & efficient handling of local loads
  - Greater control of their own micro-environment
Projecting Flow

- Disadvantages of projecting flow
  - Draft discomfort or pressure air jet
  - Limited area of environmental control
  - More complicated space air diffusion design
- Usually free jets with high entrainment ratios
  - Long-throat round nozzles are often used
- Two types of projecting flow
  - Industrial spot cooling systems
  - Desktop task air conditioning systems
Industrial spot cooling system  Desktop task air conditioning

Projecting Flow

- Industrial spot cooling systems
  - Temperature difference between target zone & the room air is often 2.8 °C or greater
  - Distance between target zone & supply outlet
  - Vertical vs horizontal jet
  - Target velocities
  - Thermal sensation
    - Of whole body & for individual parts (local)
  - Allow occupants to have individual control
Projecting Flow

• Desktop task conditioning systems
  • Also task/ambient conditioning (TAC)
  • Typical design: self-powered mixing box, small supply fans, desktop supply outlets (nozzles), flexible ducts + control panel
  • Also integration with furniture or partitions
  • Advantages:
    • Allow occupants to fine-tune the local environment
    • Possible to off the unit when unoccupied to save energy
    • Direct supply of primary air to occupants
Figure 5.1  UFAD and TAC diffuser locations in a workstation.

(Source: ASHRAE Underfloor Air Distribution Design Guide)
Figure 5.12  Underdesk TAC supply unit [Johnson Controls 2002].

(Source: ASHRAE Underfloor Air Distribution Design Guide)
Air Flow Analysis

- Computational fluid dynamics (CFD)*
  - Computing technique for analysis & prediction of fluid motion and heat transfer
    - Using Navier-Stokes & thermal equations
  - Become more and more popular for study of air flow patterns, indoor temperature distribution & indoor contaminants
  - Useful tool for studying space air diffusion

* Video: Computational Fluid Dynamics (CFD) (3:32) https://www.youtube.com/watch?v=hzTCCcsOTg8
http://www.learnengineering.org/2013/05/What-is-CFD-computational-fluid-dynamics.html
CFD visualisation – temp. distribution (St. James Theatre, Australia)

(Source: Dr. Yuguo Li, Dept of Mech Engg, HKU)
CFD visualisation – temp. distribution (Sydney Fruit Market)

(Source: Dr. Yuguo Li, Dept of Mech Engg, HKU)
Computational fluid dynamics (CFD) applied to airflow study

(Source: http://www.fluent.com/)
CFD applied to naturally ventilated buildings

(Source: http://www.flovent.com)
CFD applied to data centre design study

(Source: http://www.flovent.com)
Air Flow Analysis

• Computational fluid dynamics (CFD)
  • Turbulence modelling methods
    • Correlations, e.g. drag as a function of Re
    • Integral methods
    • Reynolds average models (κ-ε models)
      • Large eddy simulation (LES)
      • Direct numerical simulation (DNS)
  • Time average Navier-Stokes equations*
    • Incompressible form of the momentum equation
    • Full and general set of partial differential equations governing fluid motion

* Video: Computational Fluid Dynamics (CFD) | RANS & FVM (5:21) https://www.youtube.com/watch?v=YGuLvNWKk2k
http://www.learnengineering.org/2013/05/computational-fluid-dynamics-rans-fvm.html
Air Flow Analysis

- **Computational fluid dynamics (CFD)**
- **Governing equations:**
  - **Mass balance:**  \[
  \frac{\partial \rho}{\partial t} + \frac{\partial (\rho U)}{\partial x} + \frac{\partial (\rho V)}{\partial y} + \frac{\partial (\rho W)}{\partial z} = 0
  \]
  - **Momentum:**  \[
  \frac{\partial (\rho U)}{\partial t} + \frac{\partial (\rho UU)}{\partial x} + \frac{\partial (\rho UV)}{\partial y} + \frac{\partial (\rho UW)}{\partial z} = -\frac{\partial P}{\partial x} + \frac{\partial (\mu \frac{\partial U}{\partial x})}{\partial x} + \frac{\partial (\mu \frac{\partial U}{\partial y})}{\partial y} + \frac{\partial (\mu \frac{\partial U}{\partial z})}{\partial z} + \frac{1}{3} \frac{\partial}{\partial x} \left[ \mu \left( \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} \right) \right] + \rho g_x
  \]
  - **Energy:**  \[
  \frac{\partial (\rho T^*)}{\partial t} + \frac{\partial (\rho U T^*)}{\partial x} + \frac{\partial (\rho V T^*)}{\partial y} + \frac{\partial (\rho W T^*)}{\partial z} = \frac{\partial}{\partial x} \left( \Gamma \frac{\partial T^*}{\partial x} \right) + \frac{\partial}{\partial y} \left( \Gamma \frac{\partial T^*}{\partial y} \right) + \frac{\partial}{\partial z} \left( \Gamma \frac{\partial T^*}{\partial z} \right)
  \]

- **Fluid density (\(\rho\))**
- **Velocity (\(U, V, W\))**
- **Viscosity (\(\mu\))**
- **Temperature (\(T^*\))**
- **Diffusivity (\(\Gamma\))**
References

• The Basics of Computational Fluid Dynamics Modeling

• Navier-Stokes Equations (Foundations of Fluid Mechanics)
  • http://www.navier-stokes.net/

• FLOVENT Applications
  • http://www.flovent.com/applications/