Air-side Systems: Air Duct Design

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Duct Construction

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  • Exhaust air

• Duct sections
  • Header or main duct (trunk)
  • Branch duct or runout
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: \( \leq 500 \text{ Pa}, \text{ max } 12 \text{ m/s} \)
    - Medium-pressure system: 500-1500 Pa, max 17.5 m/s
  - Residential buildings: 125 Pa or 250 Pa
  - Industrial duct system: \( \Delta P \) can be higher
Duct Construction

- Duct material: e.g. UL (Underwriters’ Laboratory) standard
  - **Class 0**: zero flame spread, zero smoke developed
    - Iron, galvanized steel, aluminum, concrete, masonry, clay tile
  - **Class 1**: flame spread $\leq 25$, smoke developed $\leq 50$
    - Fiberglass, many flexible ducts
  - **Class 2**: flame spread $\leq 50$, smoke developed $\leq 100$
Duct Construction

- Shapes of air duct
  - Rectangular
    - More easily fabricated on site, air leakage
  - Round
    - Less fluid resistance, better rigidity/strength
  - Flat oval
  - Flexible
    - Multiple-ply polyester film w/ metal wire or strips
- SMACNA (Sheet Metal and Air Conditioning Contractors’ National Association) standards
Rectangular duct

Round duct w/ spiral seam

Flat oval duct

Flexible duct

Transverse joint reinforcement

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
Duct Properties

- 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 curves
    - Depends on air velocity, duct dimensions & insulation
Temperature rise from duct heat gain

Round duct
Insulation 1.5 in. duct wrap
\( k = 0.30 \text{ Btu} \cdot \text{in.} / \text{h} \cdot \text{ft}^2 \cdot ^\circ \text{F} \)
\( \Delta T = 25^\circ \text{F} \)
Length \( L = 100 \text{ ft} \)

Temperature rise \( \Delta T \), \(^\circ \text{F}\)

Duct velocity \( v \), fpm

Temperature rise from duct heat gain

Duct Properties

- **Frictional losses: Darcey-Weisbach Equation**
  - $H_f = \text{friction head loss, or } \Delta p_f = \text{pressure loss}$
  
  $$H_f = f \left( \frac{L}{D} \right) \left( \frac{v^2}{2g} \right) \quad \Delta p_f = f \left( \frac{L}{D} \right) \left( \frac{\rho v^2}{2g_c} \right)$$

  - $f =$ 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$^2$)
  - $\rho =$ density of fluid (kg/m$^3$)
  - $g_c =$ dimensional constant, for SI unit, $g_c = 1$
Duct Properties

- Frictional losses
  - Friction factor \((f)\)
    - \(\text{Re}_D\) (Reynolds number)
    - \(\varepsilon\) = absolute roughness; \(\varepsilon/D\) = relative roughness
    - Smooth duct & rough duct
  - Moody diagram
    - Laminar flow (\(\text{Re}_D < 2000\)), \(f = 64 / \text{Re}_D\)
    - Critical & transition zone
    - Turbulent flow: Rouse limit, \(\text{Re}_D = 200 / \sqrt{f(\varepsilon/D)}\)
Moody diagram
Mode of airflow when air passes over and around surface protuberances of the duct wall
Duct Properties

- Duct friction chart
  - Colebrooke formula
    \[ \frac{1}{\sqrt{f}} = -2 \log \left( \frac{\varepsilon}{3.7D} + \frac{2.51}{\text{Re}_D \sqrt{f}} \right) \]

- Roughness & temperature corrections
  - \( \Delta p_f = K_{sr} K_T K_{el} \Delta p_{f,c} \)
    - \( K_{sr} = \) 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)
<table>
<thead>
<tr>
<th>Duct Material</th>
<th>Roughness Category</th>
<th>Absolute Roughness $\varepsilon$, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncoated carbon steel, clean (Moody 1944) (0.05 mm)</td>
<td>Smooth</td>
<td>0.03</td>
</tr>
<tr>
<td>PVC plastic pipe (Swim 1982) (0.01 to 0.05 mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum (Hutchinson 1953) (0.04 to 0.06 mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galvanized steel, longitudinal seams, 1200 mm joints (Griggs et al. 1987)</td>
<td>Medium smooth</td>
<td>0.09</td>
</tr>
<tr>
<td>(0.05 to 0.10 mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galvanized steel, continuously rolled, spiral seams, 3000 mm joints (Jones 1979) (0.06 to 0.12 mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galvanized steel, spiral seam with 1, 2, and 3 ribs, 3600 mm joints (Griggs et al. 1987) (0.09 to 0.12 mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galvanized steel, longitudinal seams, 760 mm joints (Wright 1945) (0.15 mm)</td>
<td>Average</td>
<td>0.15</td>
</tr>
<tr>
<td>Fibrous glass duct, rigid</td>
<td>Medium rough</td>
<td>0.9</td>
</tr>
<tr>
<td>Fibrous glass duct liner, air side with facing material (Swim 1978) (1.5 mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fibrous glass duct liner, air side spray coated (Swim 1978) (4.5 mm)</td>
<td>Rough</td>
<td>3.0</td>
</tr>
<tr>
<td>Flexible duct, metallic (1.2 to 2.1 mm when fully extended)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexible duct, all types of fabric and wire (1.0 to 4.6 mm when fully extended)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete (Moody 1944) (1.3 to 3.0 mm)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Source: ASHRAE Handbook Fundamentals 2001)
Duct Properties

- **Circular equivalent**
  - Hydraulic diameter, \( D_h = 4 \frac{A}{P} \)
    - \( A = \text{area (mm}^2\); \( P = \text{perimeter (mm)} \)
  - 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
\[ C = \text{local loss coefficient, dimensionless} \]
\[ \Delta p_j = \text{total pressure loss, Pa} \]
\[ \rho = \text{density, kg/m}^3 \]
\[ V = \text{velocity, m/s} \]
\[ P_v = \text{velocity pressure, Pa} \]
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
FITTING LOSS COEFFICIENTS

Fittings to support Examples 8 and 9 and some of the more common fittings are reprinted here. For the complete fitting database see the Duct Fitting Database (ASHRAE 1994).

ROUND FITTINGS

CD3-1 Elbow, Die Stamped, 90 Degree, $r/D = 1.5$

<table>
<thead>
<tr>
<th>$D$, mm</th>
<th>75</th>
<th>100</th>
<th>125</th>
<th>150</th>
<th>180</th>
<th>200</th>
<th>230</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_o$</td>
<td>0.30</td>
<td>0.21</td>
<td>0.16</td>
<td>0.14</td>
<td>0.12</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
</tr>
</tbody>
</table>

CD3-3 Elbow, Die Stamped, 45 Degree, $r/D = 1.5$

<table>
<thead>
<tr>
<th>$D$, mm</th>
<th>75</th>
<th>100</th>
<th>125</th>
<th>150</th>
<th>180</th>
<th>200</th>
<th>230</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_o$</td>
<td>0.18</td>
<td>0.13</td>
<td>0.10</td>
<td>0.08</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
</tr>
</tbody>
</table>

(Source: ASHRAE Handbook Fundamentals 2001)
Region of eddies and turbulences in a round elbow

5-piece 90° round elbow

(Source: ASHRAE Handbook Fundamentals 2001)
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

Abrupt enlargement

Sudden contraction

Duct Properties

• Flow resistance, $R$
  • Total pressure loss $\Delta p_t$ 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:
    $$\frac{1}{\sqrt{R_p}} = \frac{1}{\sqrt{R_1}} + \frac{1}{\sqrt{R_2}} + \ldots + \frac{1}{\sqrt{R_n}}$$
Total pressure loss and flow resistance of a round duct section

Flow resistance in series

Flow resistance in parallel

Flow resistance for a Y connection

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

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
### Table 10  Typical Design Velocities for HVAC Components

<table>
<thead>
<tr>
<th>Duct Element</th>
<th>Face Velocity, m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOUVERS&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Intake</td>
<td></td>
</tr>
<tr>
<td>3300 L/s and greater</td>
<td>2</td>
</tr>
<tr>
<td>Less than 3300 L/s</td>
<td>See Figure 15</td>
</tr>
<tr>
<td>Exhaust</td>
<td></td>
</tr>
<tr>
<td>2400 L/s and greater</td>
<td>2.5</td>
</tr>
<tr>
<td>Less than 2400 L/s</td>
<td>See Figure 15</td>
</tr>
<tr>
<td>FILTERS&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Panel filters</td>
<td></td>
</tr>
<tr>
<td>Viscous impingement</td>
<td>1 to 4</td>
</tr>
<tr>
<td>Dry-type, extended-surface</td>
<td></td>
</tr>
<tr>
<td>Flat (low efficiency)</td>
<td></td>
</tr>
<tr>
<td>Pleated media (intermediate efficiency)</td>
<td>Up to 3.8</td>
</tr>
<tr>
<td>HEPA</td>
<td>1.3</td>
</tr>
<tr>
<td>Renewable media filters</td>
<td></td>
</tr>
<tr>
<td>Moving-curtain viscous impingement</td>
<td>2.5</td>
</tr>
<tr>
<td>Moving-curtain dry media</td>
<td>1</td>
</tr>
<tr>
<td>Electronic air cleaners</td>
<td></td>
</tr>
<tr>
<td>Ionizing type</td>
<td>0.8 to 1.8</td>
</tr>
<tr>
<td>HEATING COILS&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Steam and hot water</td>
<td>2.5 to 5</td>
</tr>
<tr>
<td>1 min., 8 max.</td>
<td></td>
</tr>
<tr>
<td>Electric</td>
<td></td>
</tr>
<tr>
<td>Open wire</td>
<td>Refer to mfg. data</td>
</tr>
<tr>
<td>Finned tubular</td>
<td>Refer to mfg. data</td>
</tr>
<tr>
<td>DEHUMIDIFYING COILS&lt;sup&gt;d&lt;/sup&gt;</td>
<td>2 to 3</td>
</tr>
<tr>
<td>AIR WASHERS&lt;sup&gt;e&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Spray type</td>
<td>1.5 to 3.0</td>
</tr>
<tr>
<td>Cell type</td>
<td>Refer to mfg. data</td>
</tr>
<tr>
<td>High-velocity spray type</td>
<td>6 to 9</td>
</tr>
</tbody>
</table>

![Graph showing face area per louver vs. air flow per louver](image)

<table>
<thead>
<tr>
<th>Parameters Used to Establish Figure</th>
<th>Intake Louver</th>
<th>Exhaust Louver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum free area (1220 mm square test section), %</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>Water penetration, μL/(m²·s) (less than 0.6)</td>
<td>Negligible</td>
<td>na</td>
</tr>
<tr>
<td>Maximum static pressure drop, Pa</td>
<td>35</td>
<td>60</td>
</tr>
</tbody>
</table>

(Source: *ASHRAE Handbook Fundamentals 2001*)
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?
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

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 $\Delta$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

Air Duct Design & Sizing

- Design information required
  - Client requirements
  - Required supply air condition
  - Type of system supplied
  - Ambient conditions
  - Duct material
  - Duct insulation
  - Duct system layout
Air Duct Design & Sizing

- Key design inputs
  - Design volume flow rate (m³/s)
  - Limiting duct pressure loss (Pa/m)
  - Limiting flow velocity (m/s)
- Design outputs
  - Schematic of ductwork layout & associated plant
  - Schedule of duct sizes and lengths, and fittings
Air Duct Design & Sizing

- Duct system characteristics
  - Supply duct, return duct, or exhaust duct systems with certain pressure loss in branch takeoffs
    - Duct sizing based on LCC & space optimisation
    - System balancing through pressure balance of duct paths
    - Sound level will be checked & analysed
    - Minimise local loss coefficients of duct fittings
    - Supply volume flow rates adjusted according to duct heat gain
Cost analysis for a duct system

Air Duct Design & Sizing

- Duct system characteristics
  - Supply duct, return duct, or exhaust duct systems in which supply outlets or return grilles either mounted directly on duct or have very short connecting duct
    - Very small or negligible pressure loss at branch ducts
    - System balancing depends mainly on sizes of the successive main duct sections
Rectangular supply duct with transversal slots

\[ \Delta p_t = (f_n L_p / D_n + C_{c,sn}) \rho v_n^2 / 2 g_c \]

\[ \Delta p_{tn} = (C_{c,bn} v_n^2 + C_{o,vn} v_o^2) \rho / 2 g_c \]

Air Duct Design & Sizing

- Duct system characteristics
  - Industrial exhaust duct systems to transport dust or other particulates
    - Require a minimum velocity in all duct sections, such as 12.2 to 20.3 m/s
    - Select proper configuration of duct fittings to provide a better system balance
      - Round ducts produce smaller losses & more rigid
      - Air velocity must not exceed too much, to avoid energy waste
      - Well-sealed joints & seams to reduce air leakage
Other Factors

- Duct liner
  - Lined internally on inner surface of duct wall
  - Mainly used for noise attenuation & insulation
  - Fiberglass blanket or boards
- Duct cleaning
  - Prevent accumulation of dirt & debris
  - Agitation device to loosen the dirt & debris
  - Duct vacuum to extract loosened debris
  - Sealing of access openings
Duct breakout noise

Other Factors

• Pressure and airflow measurements
  • Pitot tube
    • Two concentric tubes
  • Manometers
    • U tube or inclined one
• Demonstration of measuring instrument
Pitot tube

Manometer: U-value

Inclined manometer

Pressure measurements in air ducts

Measuring points in rectangular & round duct transverse