Basics of Ventilation II
Review of Phase I

North Carolina Industrial Ventilation Conference
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Prerequisite Knowledge

In Advanced Design or I&M, the attendee should already be familiar with basic air properties such as:
- Density
- Specific volume
- Density factors for
  - Temperature
  - Elevation
  - Moisture
  - Pressure

Prerequisite Knowledge

...and know basic hood nomenclature terminology and application:
- Volumetric flow rate
- Velocity (minimum duct design, capture, face, plenum, duct, and minimum transport)
- Velocity pressure (duct and slot)
- Hood static pressure

Prerequisite Knowledge

...and know what types of hoods are used in industrial ventilation:
- Simple hoods
- Compound/slotted hoods
- Enclosing hoods
- Exterior (capture) hoods
- Canopy hoods
- Push-pull hoods

...and understand the effects of slotted hoods, baffles, and flanges.

Properties of Air

Identify important properties of air.
- Density and specific volume
- Density factor at various air conditions.
- Mass flow rate
- ACFM (i.e., actual volumetric flow rate).
- Types of pressures in a ventilation system.

Density ($\rho$)

- Defined as mass/volume
- Units of measure:
  - lbm/ft$^3$
  - grams/cm$^3$ (metric)
  - grains/ft$^3$
Sea Level Density

Sea Level Specific Volume

\[ SV = \frac{1}{\rho} = \frac{1}{0.075 \text{ lbm/ft}^3} = 13.35 \text{ ft}^3/\text{lbm} \]

A pound of air will occupy 13.35 cubic feet at sea level, with no moisture, and 70 F (i.e., standards conditions).

Properties of Air

Specific Volume (SV)

- Defined as volume/mass
- Units of measure: \text{ft}^3/\text{lbm}

Problem 1

5,500 cubic feet of air flows through a duct every minute at Standard Conditions. How many pounds per minute?

\[ \frac{\text{lbm}}{\text{min}} = \left( \frac{5500 \text{ ft}^3}{\text{min}} \right) \left( \frac{0.075 \text{ lbm}}{\text{ft}^3} \right) = 412.5 \text{ lbm/minute} \]

‘Actual’ Conditions

- Standard Conditions (STP with no moisture):
  - Temperature = 70 F, and
  - Pressure = 14.7 psia, and
  - Moisture = 0 RH.
- Actual conditions are caused by changes in:
  - Temperature, and/or
  - Pressure (elevation), and/or
  - Humidity (i.e., an increase in RH)
- Where:
  - STP = standard temperature and pressure with no moisture
  - psia = pounds per square inch atmospheric
  - RH = relative humidity (i.e., moisture content)
‘Actual’ Conditions

- Any condition where the air is not at Sea Level, 70 F, and carries no moisture.
- It is significant in our work if:
  - Temperature > 100 F
  - Elevation > 1000’ ASL
  - Dew Point > 80 F
- Industrial Ventilation Design Manual, page 3-14

Problem 2

7,500 actual cubic feet of air flows through a duct every minute at a density of 0.043 lbm/ft³. What is the mass flow rate in lbm per minute?

\[
\frac{\text{lbm}}{\text{min}} = \left( \frac{7500 \text{ ft}^3}{\text{min}} \right) \left( \frac{0.043 \text{ lbm}}{\text{ft}^3} \right) = 322.5 \text{ lbm/minute}
\]

The Perfect Gas Law

- Knowing the mass a gas, then the density and the volume it occupies will be a function of:
  - The pressure the gas sees (i.e., absolute Pressure).
  - The temperature of the gas (i.e., absolute Temperature).
  - The presence of moisture or any other material mixed with the gas.
- Equation used in this course: \( P = \rho R_g T \)

P = \( \rho R_g T \)

- \( R_g \) is the Gas Constant unique for a particular gas:
  \[ R_g = \frac{R_u}{M} \]
- \( R_u \) = Universal Gas Constant = 1545.4 ft-lbf/lbm R
- \( M \) = Molecular Weight of the gas
- IV Design Manual, Appendix B, page 14-23

Density of Standard Air

- \( M_{air} = 28.96 \text{ lbm/mole} \)
- Pressure at Sea Level = 14.7 psi
- \( T_{STD} = 70 \text{ F} = (460 + 70) \text{ R} = 530 \text{ R} \)
- \( R_u = 1545.4 \text{ ft-lbf/mole-R} \)
- \( R_g = 53.36 \)
- \( P = \rho RT \rightarrow \rho = \frac{P}{RT} \)

Density Factor (df)

Defined as the ratio of actual density to standard density

\[
df = \left( \frac{\rho_{act}}{\rho_{std}} \right) = \left( \frac{\rho_{act}}{0.075 \text{ lbm/ft}^3} \right)
\]

IV Design Manual, page 3-14
**Density Factor Components**

- Temperature: \( df_T = \frac{T_{std}}{T_{act}} = \frac{\rho_{std}}{\rho_{act}} \)
- Elevation: \( df_e = [1 - (6.73 \times 10^{-6})(z)]^{5.258} \)
- Moisture: \( df_m = \text{psychrometric charts} \)
- Pressure: \( df_p = \left(\frac{407 + SP_{duct}}{407}\right) \)

- Density Factor \((df) = df_T \times df_e \times df_m \times df_p\)

**Problem 3: Density Factor**

Air enters a fan at 280°F and -28" wg pressure. The Fan is located at 3200' ASL. What is the Density Factor of the Air at the fan inlet?

- \( df_T = \frac{530}{(460 + 280)} = 0.72 \)
- \( df_e = [1 - (6.73 \times 10^{-6})(3200)]^{5.258} = 0.89 \)
- \( df_m = 1 \) (no moisture)
- \( df_p = \left(\frac{407 - 28}{407}\right) = 0.93 \)

- \( df = df_T \times df_e \times df_m \times df_p = 0.60 \)

**Relationship between Mass Flow Rate and CFM**

\[
\left(\frac{\dot{m}_{min}}{\text{lbm}}\right) = \left(\frac{\dot{m}_{min}}{\text{lbm}}\right) = (Q_k \rho)
\]

\[
\left(\frac{\dot{m}_{tot}}{\text{lbm}}\right) = (Q_{act}) = (Q_{std})(1 + \omega)
\]

**Actual Volumetric Flow Rate \((Q_{act})\)**

- \( Q_{act} = Q_{std} \times \left(\frac{1}{df}\right)(1 + \omega) \)

**Why ACFM?**

- Used to size the Air Control Device correctly
- Used to size the duct correctly
- Used to size the Fan correctly
Problem 4

ACFM

4,100 lbm of air at standard conditions enters a dryer where it picks up 320 lbm/minute of water and leaves with a density factor of 0.72:

What is the Air Volume \( Q_{act} \)?

\[
Q_{act} = \frac{4,100 \text{ lbm} + 0.075 \text{ lbm/ft}^3 \times 320 \text{ lbm/minute}}{0.075 \text{ lbm/ft}^3} = 54,667 \text{ scfm}
\]

\[
(ACFM) = 54.667 \left( \frac{1}{0.72} \right) \left( 1 + \frac{320}{4100} \right)
\]

\[
(ACFM) = 81,852 \text{ ACFM}
\]

\@ \, df = 0.72

Three Pressures at any Point in a Duct System

Comparison to Atmospheric (+/-)

Greater Than Atmospheric (+)

Less Than Atmospheric (-)

Velocity Pressure \( \Rightarrow \) Velocity

\[ VP = df \left( \frac{V}{4005} \right) \]

- VP:
  - Equals \( TP - SP \)
  - Cannot be measured directly
  - Represents kinetic energy

V = 4005 \( \sqrt{\frac{VP}{df}} \)

Where:
- \( V \) = velocity in fpm
- \( VP \) = Velocity Pressure in "wg
- \( df \) = density factor

Static Pressure Losses

(hood) \( F_h \)\( VP_h \)
(compound hood) \( \left[ F_p \right] \)\( VP_p \)
(acceleration) \( 1VP \)
(duct friction) \( F_d \)\( VP_d \)
(elbows) \( F_e \)\( VP_e \)
(entries) \( F_{en} \)\( VP_{en} \)
(\( F_{special\ fitting} \))\( VP_{sp} \)

Other Losses = air pollution control device, loss from velocity increase, etc.

System Components

- Hoods
- Ducts
- Air pollution control equipment
- Fans
- Exhaust stack
Design of Local Exhaust Hoods

- When we can predict the location of a release of dust or other contaminant, we can pull a small amount of air immediately next to the source to remove the contaminant effectively.

- Poor hood design can lead to:
  - Poor contaminant control,
  - BIG air pollution control equipment costs ($$$),
  - BIG replacement air costs ($$$), and
  - BIG fans with BIG motors ($$$).

- The challenge is to remove the smallest amount of air with the greatest concentration of pollutant!

Hood Refresher

- \( Q = VA \)
- Capture velocity
- Minimum transport velocity
- ‘Acceleration’ loss (not really acceleration – it is energy transfer)
- Flanges and affects on airflow
- Air Volume Requirements

Hood Types

- \( SP_H = h_v + VP \)
- Where:
  - \( h_v = \left( \frac{F_h}{VP_v} \right) \), or
  - \( h_v = \left( \frac{F_h}{VP_v} \right) + \left( \frac{F_s}{VP_s} \right) \), for compound hoods
  - \( F_h = \) hood entry loss coefficient
  - \( F_s = \) slot loss coefficient
  - \( VP_v = \) duct velocity pressure in “wg
  - \( VP_s = \) slot velocity pressure in “wg

Problem 5

Find \( Q_{act} \), where:

\[ VP = 0.78 \text{ "wg} \]
\[ df = 0.89 \text{ (no moisture – i.e., } \omega = 0) \]
\[ D = 6 \text{ inches} \]
\[ \omega = 4005 \times (VP/df)^{0.5} = 4005 \times (0.78/0.89)^{0.5} = 3,748 \text{ fpm} \]
\[ Q_{act} = \frac{VA}{D} = \frac{3,748 \times 0.1963}{1} = 736 \text{ ACFM} \]
\[ Q_{act} = \frac{Q_{std} \times (1/df) \times (1 + \omega)}{D} = \frac{736 \times (1/0.89) \times (1)}{6} = 655 \text{ SCFM} \]

Problem 6

Given a flanged slotted hood for a welding operation in an area with disturbing air currents, where:

\[ df = 0.76 \text{ (no moisture – i.e., } \omega = 0) \text{ and } 90^\circ \text{ included angle} \]
\[ A = 2.41 \text{ ft}^2 \text{ and } X_{source} = 1.5 \text{ ft} \text{ and } D_{duct} = 16" \]

\[ V_{capture} = \frac{0.75V(10X^2 + A)}{(10X^2 + A)} = \frac{(0.75)(200)[(10(1.5)^2 + 2.41)]}{(10(1.5)^2 + 2.41)} = 3,736 \text{ SCFM} \]

\[ Q_{act} = Q \times (1/df) \times (1 + w) = (3,736/0.76) \times (1) = 4,916 \text{ ACFM} \]

\[ SP_{hood} = 1.78 \text{ "wg} \text{ and } \frac{VP_{hood}}{VP_{hood}} = 0.59 \text{ "wg} \]

\[ Q_{act} = 3,736 \text{ SCFM} \]

\[ Q_{std} = \frac{3,736}{0.76} \times (1) = 4,916 \text{ ACFM} \]

\[ F_{entry} = 1.78 \text{ "wg} \text{ and } F_{slot} = 0.59 \text{ "wg} \]

\[ SP_{hood} = 1.78(0.20) + 0.25(0.59) + 0.59 = 1.09 \text{ "wg} \]
System Component Losses

(hood) (F_h)(V_p)
(compound hood) [(F_h)(V_p)]
("acceleration") I_VP
(duct friction) (F_d)(V_p)
(entries) (F_e)(V_p)

+ ("Special fittings") (V_p)

Other Losses \( \Delta P \) - Static Pressure

Elbows

- "F_e" is a function of:
  - R/D
  - Number of pieces
  - Degree of turn (e.g., 45°, 90°)
  - 90° called 'elbows'
- < 90° called 'angles' (e.g., 30°, 45°, 60°)
- Recommended R/D?

Branch Entries

- \( F_{en} \) is a function of:
  - Angle of Entry
  - Looking for efficiency (lowest \( F_{en} \))
  - Recommended angle < 45°
  - 30° and 45° are most common
- Least Efficient (90°)
- Most Efficient (<10°)

Straight Duct

- \( SP = F_d(V_p) \)
- Losses are a function of:
  - Length of duct
  - Diameter of duct (smaller diameter has more friction)
  - Speed of air through the duct
- \( F_d = \frac{(0.0307)(V)^{0.533}}{(Q)^{0.612}} \)

Contractions and Expansions

- Use for:
  - Fitting ducts into tight places
  - Fit equipment
  - Provide high discharge velocity at end of stack
  - Contractions increase the duct velocity – erosion considerations in particulate conveying systems
  - Expansions decrease the duct velocity – minimum transport considerations in particulate conveying systems
  - Energy loss or regain a function of geometry of the transition piece

Problem 7

Contractions and Expansions

Calculate the static pressure losses through the system and properly size the orifice (at standard conditions).
Problem 7
Contractions and Expansions

Losses for Segment 1-A:

\[ V = \frac{Q}{A_{1-A}} = 9,500 \text{ cfm/2.6398 ft}^2 = 3,599 \text{ fpm} \]

\[ V_Pd = \frac{df(V/4005)^2}{(1)(3,599/4,005)^2} = 0.81 \text{ "wg} \]

\[ SP_h = \frac{F_d V_Pd + 1V_P}{V_Pd(1 + F_d)} = 0.81(1 + 0.49) = 1.20 \text{ "wg} \]

\[ F_d = 0.0307\left(\frac{V^{0.533}}{Q^{0.612}}\right) \quad \text{(or use Table 9-4)} \]

\[ = 0.0307\left(\frac{3,599^{0.533}}{9500^{0.612}}\right) = 0.0089 \]

\[ SP_{\text{Duct Friction}} = (F_d)L(V_Pd) = 0.0089(1)(0.81) = 0.72 \text{ "wg} \]

\[ SP_{1-A} = (SP_h + SP_{\text{Duct Friction}}) = (1.2 + 0.72) = -1.92 \text{ "wg} \]

Problem 7
Contractions and Expansions

Losses for Contraction (Figure 9-d):

\[ SP_2 = SP_1 - (V_P2 - V_P1) - L(V_P2 - V_P1), \text{ where...} \]

\[ SP_1 = -1.92 \text{ "wg} \]

\[ V_P1 = 0.81 \text{ "wg} \]

\[ V_P2 = \frac{df(V/4005)^2}{(1)(5,376/4,005)^2} = 1.80 \text{ "wg} \]

\[ L = 0.08 \text{ (for 15 degree taper angle)} \]

\[ SP_2 = -1.92 - (1.80 - 0.81) - 0.08(1.80 - 0.81) \]

\[ = -2.99 \text{ "wg} \text{ (SP at exit from contraction)} \]

Problem 7
Contractions and Expansions

Regain for Expansion (Figure 9-d):

\[ SP_2 = SP_1 + R(V_P1 - V_P2), \text{ where...} \]

\[ SP_1 = -3.19 \text{ "wg} \]

\[ V_P1 = 1.80 \text{ "wg} \]

\[ V_P2 = 0.81 \text{ "wg} \]

\[ R = 0.83 \text{ (15 degree taper angle; } D_2/D_1 = 1.22) \]

\[ SP_2 = -3.19 + 0.83(1.80 - 0.81) = -2.37 \text{ "wg} \text{ (SP at exit from expansion)} \]

Problem 7
Contractions and Expansions

Losses for Segment 1-C:

\[ SP_{\text{Expansion Exit}} = -2.37 \text{ "wg} \]

\[ V_{B-C} = 3,599 \text{ fpm} \]

\[ V_P_{B-C} = 0.81 \text{ "wg} \]

\[ F_d = 0.0089 \]

\[ SP_{\text{Duct Friction}} = (F_d)L(V_Pd) = 0.0089(1)(0.81) = 0.29 \text{ "wg} \]

\[ SP_{1-C} = (SP_{\text{Duct Friction}} + SP_{\text{Expansion Exit}}) \]

\[ = (0.29 + 2.99) = -3.26 \text{ "wg} \]

Problem 7
Contractions and Expansions

Orifice Design:

\[ (SP_h + SP_{\text{Duct Friction}}) = -2.66 \text{ "wg} \]

\[ V = \frac{Q_{2-C}/A_{2-C}}{3,000 \text{ cfm/1.3963 ft}^2} = 2,149 \text{ fpm} \]

\[ VP = \frac{df(V/4005)^2}{(1)(2,149/4,005)^2} = 0.29 \text{ "wg} \]

\[ F_d = 0.0307\left(\frac{V^{0.533}}{Q^{0.612}}\right) \quad \text{(or use Table 9-4)} \]

\[ = 0.0307\left(\frac{2,149^{0.533}}{9500^{0.612}}\right) = 0.0137 \]

\[ SP_{\text{Duct Friction}} = (F_d)L(V_Pd) = 0.0137(2)(0.29) = 0.08 \text{ "wg} \]

\[ SP_h = 2.66 - SP_{\text{Duct Friction}} = 2.66 - 0.08 = -2.58 \text{ "wg} \]
Problem 7
Contractions and Expansions

Orifice Design:

\[ SP_h = 2.66 - SP_{d duct friction} = 2.66 - 0.08 = -2.58 \text{ "wg} \]

\[ SP_h = F_{orifice} + 1VP_p \]

\[ VP_{orifice} = (2.58 - 0.29)/1.78 = 1.29 \text{ "wg} \]

\[ V_{orifice} = 4005(VP/df)^{0.5} = 4005(1.29/1)^{0.5} = 4549 \text{ fpm} \]

\[ A_{orifice} = Q_{orifice}/V_{orifice} = 3,000 \text{ cfm}/4549 \text{ fpm} = 0.6659 \text{ ft}^2 \]

\[ D_{orifice} = (4 \times 144 \times A_{orifice}/\pi)^{0.5} = (4 \times 144 \times 0.6659/\pi)^{0.5} = 11 \text{ inches} \]

Using the Calculation Sheet

Using the results from Problem 7, input the data for segment 1-A into a calculation sheet.

ACGIH Calculation Sheet

Calc Sheet – Q, V, D, and VP

Calc Sheet – Hoods

Calc Sheet – Duct, Elbow, Entry Losses
Calc Sheet – Other Losses; SP; Corrected Q, V, and VP

<table>
<thead>
<tr>
<th>#</th>
<th>Description</th>
<th>SP</th>
<th>Q0</th>
<th>V0</th>
<th>VP</th>
</tr>
</thead>
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<td>40</td>
<td>Other Losses</td>
<td>8.38</td>
<td>0.38</td>
<td>-0.20</td>
<td></td>
</tr>
</tbody>
</table>

Balancing Methods

- **With blast gates**
  - **Advantages**
    - Adjustable
    - Design flexibility
  - **Disadvantages**
    - Not tamper-proof
    - Higher initial cost
- **Balance-by-design**
  - **Advantages**
    - No tampering
    - No blast gates to wear
  - **Disadvantages**
    - Higher airflows

Balancing Branch SP at Entries

- **Q1 + Q2 = Q3**
- **SP1 = SP2 = SP3**
- **Adjustments:**
  - No adjustment (SPcorr < 5%)
  - Calculate Qcorr, Vcorr, and VPcorr for branch with lower SP (5% ≤ SPcorr ≤ 20%)
  - Redesign branch with lower SP (SPcorr > 20%)

  ![Balancing Branch SP at Entries Diagram](image)

Accounting For Acceleration at Branch Entries

**Weighted Average VP**

- **VPi = (VPi)(Qi/Q3) + (VPj)(Qj/Q3)**
- Used to be called Resultant Velocity Pressure
- Now, more correctly named: Weighted Average Velocity Pressure

Exhaust Stacks

- **Do not use weather caps!**
  - Losses associated with them
  - May also have other system effects
- **No-loss stacks**
  - Stack diameter = D + 1”
  - Stack height = 4D + 6”
  - D = duct diameter
  - Maintain discharge velocity of > 3,000 fpm

![Exhaust Stacks Diagram](image)
System Static Pressure

- The amount of pressure required by the fan to overcome the resistance in the system
- Determined by data from the calculation sheet
- System \(SP = SP_{out} - SP_{in} - VP_{in}\)
- Basis for selection of the Fan Static Pressure (FSP)

Summary

- Goal: The attendee will identify the important concepts from Phase 1 important in industrial ventilation system design.
- Identify important properties of air.
  - Calculate density and specific volume.
  - Calculate the density factor at various air conditions.
  - Calculate the mass flow rate.
  - Calculate the ACFM (i.e., actual volumetric flow rate).
  - Identify the types of pressures in a ventilation system.

Objectives – 2

- Apply and perform basic hood calculations at various conditions.
- Be able to find appropriate information in the Industrial Ventilation Design Manual.
- Be able to calculate \(Q, V,\) and \(A\) given various conditions.
- Be able to calculate the hood entry loss factor.

Objectives – 3

- Apply and perform basic ventilation system design calculations at various conditions.
  - When a branch entry occurs in a ventilation system, be able to identify when to calculate \(Q_{corr}\) versus redesign a branch.
  - Be able to calculate the weighted average velocity pressure and properly apply it at branch entries.
  - Be able to calculate a properly sized no-loss stack.
  - Be able to calculate system static pressure.

Questions and Quiz