Best Practices for Modeling Exhaust Dispersion

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OUTLINE

- Background Information
- General Description of Air Flow Around Building
- Qualitative Information on Acceptable Exhaust/Intake Designs
- Concentration Design Criteria
- Dispersion Modeling Methods
- Typical Results
Accidental Spills
Exhaust Dispersion
Exhaust Evaluation Approach

Air quality acceptability question:

\[ C_{max} < ? C_{health/odor} \]

Environmental Performance Criteria (LEEDS) Credit 9.1
-- Meet all standards and generally accepted guidelines for outdoor protection of workers and general public from airborne chemical, radioactive and biological hazards. Use mathematical modeling, physical modeling and/or post construction testing and certification to prove compliance.
Knowledge Needed

- Air flow around buildings
- Concentration design criteria for health and odors
- Dispersion model predictions
Airflow Around Buildings
Visual of Air Flow Around Building
Corner Vortex
Plume impact on taller downwind building
Plume impacting taller upwind building
Qualitative Information on Exhaust/Intake Designs
Stack Design Standards/ Codes/ Practices

- Exhaust system shall discharge at a point where it will not cause a nuisance and from which it cannot be readily drawn in by a ventilating system (IMC).
- ANSI/AIHA Z9.5 & NFPA 45 – minimum of 10 ft to protect rooftop workers.
- EPA - GEP stack height (2.5 times the building height above ground).
Manifolded exhaust system
Ganged Stacks
Increased stack height
On tallest building
Increased separation distance
Vertically Directed and No Caps
Consider effect of screens (ASHRAE – Chapter 43)
**High Enough Exhaust Velocity**

- 1.5 times the 1 % wind speed at stack top (ASHRAE 2003, Chapter 43).
Locate intakes behind building feature
(current ASHRAE research)
Air intake locations – below stack for centralized exhausts
Air intake locations – not in mechanical well with exhausts
Air intake locations – away from loading docks
Concentration Design Criteria for Health and Odor
Concentration Design Criteria

Information to develop \((C/m)_{health/odor}\)

- \(C_{health}\) & \(C_{odor}\) for each substance
- Maximum \(m\) for each substance
ASHRAE 110 Fume Hood Manikin Test

4 lpm spill
0.05 ppm at Manikin
1:3000 dilution or
700 ug/m3 per g/s
ASHRAE 1999 Fume Criteria for Intake

7.5 L/s and
3 ppm at
Intake

Equivalent to
400 ug/m3 per g/s
<table>
<thead>
<tr>
<th>Substance</th>
<th>CAS #</th>
<th>Rate Limit (g/s)</th>
<th>Emission Limit (mg/m³)</th>
<th>Type</th>
<th>Agency</th>
<th>Health Limit (mg/m³)</th>
<th>Normalized Limit (µg/m³)/(g/s)</th>
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<tbody>
<tr>
<td>Nickel carbonyl (as Ni)</td>
<td>13463-39-3</td>
<td>5.841</td>
<td>0.01</td>
<td>TWA</td>
<td>OSHA</td>
<td>0.021</td>
<td>3.6</td>
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<td>Sulfur pentafluoride</td>
<td>5714-22-7</td>
<td>15.485</td>
<td>0.10</td>
<td>Ceil</td>
<td>ACGIH</td>
<td>0.100</td>
<td>6.5</td>
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<tr>
<td>Chromyl chloride</td>
<td>14977-61-8</td>
<td>0.437</td>
<td>0.00</td>
<td>TWA</td>
<td>NIOSH</td>
<td>0.003</td>
<td>6.9</td>
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<td>Osmium tetroxide</td>
<td>20816-12-0</td>
<td>0.304</td>
<td>0.00</td>
<td>STEL</td>
<td>ACGIH</td>
<td>0.005</td>
<td>15.5</td>
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<td>Pentaborane</td>
<td>19624-22-7</td>
<td>1.371</td>
<td>0.03</td>
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<td>NIOSH</td>
<td>0.030</td>
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<td>Chloromethyl ether(bis-)</td>
<td>542-88-1</td>
<td>0.375</td>
<td>0.00</td>
<td>TWA</td>
<td>ACGIH</td>
<td>0.014</td>
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<td>Methyl isocyanate</td>
<td>624-83-9</td>
<td>2.158</td>
<td>0.05</td>
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<td>ACGIH</td>
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<td>Dimethylhydrazine(1,1-)</td>
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<td>1.025</td>
<td>0.15</td>
<td>STEL</td>
<td>NIOSH</td>
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<td>Methyl hydrazine</td>
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<td>STEL</td>
<td>NIOSH</td>
<td>0.080</td>
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<td>Bromine pentafluoride</td>
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<td>6.273</td>
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<td>2.100</td>
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<td>Tetramethyl lead (as Pb)</td>
<td>75-74-1</td>
<td>0.668</td>
<td>0.08</td>
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<td>OSHA</td>
<td>0.225</td>
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<td>Tungsten hexafluoride</td>
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<td>24.519</td>
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<td>Bromine</td>
<td>7726-95-6</td>
<td>2.986</td>
<td>1.30</td>
<td>STEL</td>
<td>ACGIH</td>
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<td>Ethyl mercaptan</td>
<td>75-08-1</td>
<td>2.982</td>
<td>1.30</td>
<td>Ceil</td>
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<td>Acrolein</td>
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<td>0.69</td>
<td>STEL</td>
<td>ACGIH</td>
<td>0.690</td>
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<td>Tetranitromethane</td>
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<td>0.04</td>
<td>TWA</td>
<td>ACGIH</td>
<td>0.120</td>
<td>704.5</td>
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Dispersion Modeling Methods

- ASHRAE Graphical Method
- EPA/ASHRAE Dispersion Equations
- CFD Modeling
- Wind Tunnel Modeling
ASHRAE Graphical Method – Not Recommended.
No Comparison with Health or Odor Limits Provided – No Dispersion Modeling
**EPA and ASHRAE Dispersion Equations**

\[ C = \frac{m}{\{\pi \sigma_y \sigma_z U_s\}} \exp\left[- \frac{H^2}{2 \sigma_z^2}\right] \times 10^6 \]

- **Site and Design Effects Term**
  \[ \frac{1}{\{\pi \sigma_y \sigma_z U_s\}} \]

- **Energy Term**
  \[ m \times \exp\left[- \frac{H^2}{2 \sigma_z^2}\right] \]
Plume Rise Predictions
Also an Main Energy Factor

\[ H = h_s + \left[ 3 F_m \times \left( \beta_j^2 U_s^2 \right) \right]^{1/3} \]

\[ \sim h_s + \text{Fan Horsepower} \]
Analytical Methods With Concentration Estimates

- Applicable for simple buildings with no taller surrounding buildings/features with air intakes on the building roof.
- Experienced professional can develop conservative exhaust designs.
- Method may not be conservative if used by inexperienced practitioner.
- Concentration estimates on building sidewalls highly inaccurate.
CFD (Computational Fluid Dynamics)
Solving The Basic Equations of Motion

- Some say this is the latest and greatest.
- What does the scientific community say?
STUDY OBJECTIVES

- Evaluate the variability of results due to the way in which a CFD code is applied.
- Evaluate the accuracy of CFD predictions in large, complex dispersion scenarios.
**APPROACH**

**Evaluation of Modeling Uncertainty**

- Four organization used CFD to evaluate the same realistic test cases.
- Same CFD code used (STAR-CD)
- Wind tunnel experiments of test cases carried out.
- CFD results compared to wind tunnel.
RESULTS
Evaluation of Modeling Uncertainty

- Variability between different modeller’s results was substantial
- CFD calculations varied between a factor of 5 and 100 from experiment
- Best agreement for simpler problems
RESULTS (CONTINUED)

- Human factors (familiarity with code, user errors)
- Numerical accuracy (different meshes and numerical schemes, available computing power)
- The atmospheric boundary layer.
Simple Building Results - Cowan, Castro and Robins, 1997
Simple Building Results
Cowan, Castro and Robins, 1997

![Graph showing experimental (Expt) and computational fluid dynamics (CFD) results for $\frac{(C U_h H^2)}{Q_s}$ vs. $y/H$.](image)
“In spite of some interesting and visually impressive results produced with CWE, the numerical wind tunnel is still virtual rather than real”

“Practitioners should be warned about the uncertainties of the numerical wind tunnel (CFD) results and urged to exercise caution in their utilization”
CWE97 - Leitl, Kline, Rau and Meroney

![Wind Tunnel Experiment - Ke](image)

ABC
ASMUS
DASIM
MISKAM
FLUENT

- Kn/Ke=1
- Kn/Ke=2/0.5
- Kn/Ke=5/0.2
- Kn/Ke=10/0.1
Wind Tunnel Modeling
Basic equations are solved by simulating the flow at a reduced scale, then measuring the desired quantity.

An analog computer with near infinitesimal resolution and near infinite memory.

If a mathematical model cannot simulate the results of an idealized laboratory experiment, how can it possibly be applicable to the atmosphere.”
**Compares Well With the Atmosphere**

- Wind and turbulence profiles consistent with underlying surface roughness.
- Plume height and width match boundary layer theory and consistent with surface roughness.
- Measured concentrations are steady-state averages (e.g. 15 minutes)
- The above has been documented.
Wind Tunnel Modeling

- Used to Validate CFD and Analytical Methods
- Controlled Meteorological Conditions
- Results Sensitive to Design Changes
- Like a Field Study
CFD and Wind Tunnel Comparison

- **Basic equations of motion solved**
  - CFD: yes but turbulence closure is approximate.
  - WT: yes and turbulence is accurately modeled.

- **Validation against field data bases**
  - CFD: ?
  - WT: yes. The wind tunnel is also used to validate CFD and analytical techniques.

- **Dispersion comparability with atmosphere demonstrated.**
  - CFD: ? EPA is working on this
  - WT: yes
CFD and Wind Tunnel Comparison

- **Standard method of application.**
  - CFD: no. EPA is working on this.
  - WT: yes. EPA has guidelines.

- **Provides conservative estimates**
  - CFD: ?
  - WT: yes.
Steps in Conducting a Wind Tunnel Study

- Construct Scale Model
- Specify Model Operating Conditions
- Setup and Visualization
- Measure Concentrations
- Compare Results with Design Criteria
- Reporting
NREL Model in Tunnel
Steps in Conducting a Wind Tunnel Study

- Construct Scale Model
- Specify Model Operating Conditions
Inputs that are needed

- Stack height/location
- Exhaust flow
- Exhaust velocity
- Exhaust temperature
- Intake locations/flows
- Site wind conditions
Steps in Conducting a Wind Tunnel Study

- Construct Scale Model
- Specify Model Operating Conditions
- Setup and Visualization
Wind tunnel
LBL MF
In CPP Wind Tunnel
NREL Flow Visualization
Concentration Measurements
Continuous Total Carbon Analyzer
Concentration Measurements

Tracer from stack

Sample withdrawn from intake
Typical Results
Referenced to the ASHRAE 400 ug/m\(^3\) per g/s Criteria
LBL MF
20 ft, 28000 cfm, 3579 fpm; Max C/m = 457 @ Roof
Wind Direction – S; Wind Speed = 8 m/s
LBL MF
30 ft, 28000 cfm, 3579 fpm; Max C/m = 209 @ Roof
Wind Direction – S; Wind Speed = 8 m/s
LBL MF
10 ft high, 10000 cfm, 1930 fpm; Max C/m = 552 @ Plaza
Wind Direction – S; Wind Speed = 2 m/s
NREL S&TF
20 ft, 16500 cfm, 2954 fpm; Max C/m = 313 @ Intake
Wind Direction – ESE; Wind Speed = 12 m/s
NREL SERF
35.8 ft, 35000 cfm, 3033 fpm; Max C/m = 89 @ Intake
Wind Direction – WSW; Wind Speed = 5 m/s
New Lab
Strobic Exhaust (46,000 cfm); Max C/m = 184 @ Roof
Wind Direction – NE; Wind Speed = 11.3 m/s
New Lab
Strobic (4500 cfm) alone; Max C/m = 1410 @ Roof
Wind Direction – SW; Wind Speed = 9 m/s
New Lab
Strobic (4500 cfm) with others; Max C/m = 393 @ Roof
Wind Direction = SW; Wind Speed = 11.3 m/s
New Lab
Strobic (28,500 cfm); Max C/m = 635 @ Intake
Wind Direction –– NE; Wind Speed = 7 m/s
New Lab
Upblast (1000 cfm); Max C/m = 2836 @ intake
Wind Direction – SE; Wind Speed = 9 m/s
Where Does This Fit in to Benefits of Labs21 Approach

- Reduced operating costs.
- Improved environmental quality.
- Expanded capacity.
- Increased health, safety, and worker productivity.
- Enhanced community relations.
- Superior recruitment and retention of scientists.
Summary –
Modeling Exhaust Dispersion

- Understand complexity of air flow
- Use general guidelines to start
- Avoid graphical methods
- Caution when using analytical or CFD methods
- Wind tunnel modeling most accurate
- Use dispersion modeling to ensure concentration design criteria are met