Consumer-grade IAQ sensors: Complications of $CO_2$ ventilation measurements

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Disclaimer

• *Certain commercial equipment, instruments, websites, or materials are identified in this paper. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.*
Educational Tools

• Ownership

• Action
  • Source removal
  • Ventilation
  • Filtration
Educational Tools

https://twitter.com/search?q=CO2&src=typed_query
https://twitter.com/mdc_martinus/status/134433266749663328/photo/1
https://twitter.com/corinne_depagne/status/1359530352809807874/photo/1
https://twitter.com/MsWinkel/status/1362401750766870529/photo/1
https://twitter.com/COVID_Airborne/status/1362825292461539332
https://twitter.com/maracarrion6/status/1362717214160396304/photo/1
https://twitter.com/citlars/status/1352734920645373952/photo/1
https://twitter.com/CO2Guerrillas/status/1352731133385953738/photo/1

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What does it all mean?

- Health values
  - Time Weighted/Instantaneous
- Accuracy/Precision
- Ventilation
Performance of low-cost indoor air quality monitors for PM$_{2.5}$ and PM$_{10}$ from residential sources

Zhiqiang Wang $^1$, William W. Delp $^2$, Brett C. Singer $^2$
Test Method for Evaluating PM$_{2.5}$ Monitors

- **Class III FEM Reference Monitor**
  - 20 nm to 20 μm
  - Gravimetrically calibrated

- **Challenge PM$_{2.5}$**
  - Sodium chloride (1.5 μm to 1.8 μm)
  - Polystyrene latex spheres (1 μm)

- **Chamber system**
  - Steady state values

- **Process**
  - Five step concentration ramp
    - 10 μg m$^{-3}$ to 300 μg m$^{-3}$
    - Inorganic then organic
  - RH and Temp variation
    - 40 % to 80 %
    - 20 °C and 30 °C
  - Interferent testing
    - Arizona Test Dust (PM$_{10}$)
      - 10 μg m$^{-3}$ to 150 μg m$^{-3}$
  - Temperature cycling
    - 10 °C to 50 °C 143 times
  - Repeating concentration ramp
Test Method for Evaluating CO$_2$ Monitors

- **Reference Monitor**
  - 0 ppm$_v$ to 10,000 ppm$_v$
  - Calibrated to certified cylinder
  - Drying system

- **Chamber system**
  - Steady state values

- **Process**
  - Five step concentration ramp
    - 450 ppm$_v$ to 5,000 ppm$_v$
  - RH and Temp variation
    - 40% to 80%
    - 20°C and 50°C
  - Interferent testing
    - Relative humidity 20% to 90%
  - Temperature cycling
    - 10°C to 50°C 143 times
  - Repeating concentration ramp

Consumer-grade sensors report concentrations in ppm$_v$. SI units are $\mu g$ m$^{-3}$. 1000 ppm$_v$ CO$_2$ = 929 $\mu g$ CO$_2$ m$^{-3}$ at 25°C and 1 atm.
So that will be it then, right?

- Just data. Need accreditation organizations.
- Re-zeroing algorithms for CO$_2$
- Long term drift?
  - 1 year plus?
Using CO$_2$ as a Ventilation Clue

The story of 10 Complications
Using CO$_2$ as a Ventilation Clue

Complication #1
Using CO$_2$ as a Ventilation Clue

https://drive.google.com/file/d/1jFavucO98vMz5_LpKtnDXBfDzvWIMLcL/view

Using CO₂ as a Ventilation Clue

Risk of indoor airborne infection transmission estimated from carbon dioxide concentration
S. N. Rudnick, D. K. Milton

Rebreathed Fraction = \( \frac{C_{\text{average}} - C_{\text{outside}}}{C_{\text{breath}}} \)

\[
Rebreathed \text{ Fraction} = \frac{(800 \text{ ppm}_v - 420 \text{ ppm}_v)}{38,000 \text{ ppm}_v}
\]

Rebreathed Fraction = 1.0 %

\( C_{\text{average}} = 2,000 \text{ ppm}_v \Rightarrow 4.2\% \)

Consumer-grade sensors report concentrations in ppm\(_v\). SI units are µg m\(^{-3}\). 1000 ppm\(_v\) CO₂ = 929 µg CO₂ m\(^{-3}\) at 25 °C and 1 atm.
Using CO$_2$ as a Ventilation Clue

Complication #2
Using CO$_2$ as a Ventilation Clue

Complication #3

650 ppm

Data from student lab at Humboldt State University
Using CO$_2$ as a Ventilation Clue

Complication #4
Using CO$_2$ as a Ventilation Clue

Complication #5
Using CO$_2$ as a Ventilation Clue

https://drive.google.com/file/d/1jFavucO98vMz5_LpKtnDXfDZvWIIMLcL/view

# Using CO$_2$ as a Ventilation Clue

<table>
<thead>
<tr>
<th>Space</th>
<th>Occupancy</th>
<th>Ventilation Rate ASHRAE 62.1 (L/s/person)</th>
<th>Outdoor Air Change rate (h$^{-1}$)</th>
<th>Steady State or Mean Peak CO$_2$ Concentration ppm$_v$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal Classroom Meeting Standards (5- to 8-year-olds)</td>
<td>24 students 1 instructor</td>
<td>7.4</td>
<td>~2.6$^a$</td>
<td>828$^b$</td>
<td></td>
</tr>
<tr>
<td>10 Actual California Classrooms</td>
<td>N/A</td>
<td>2.6 – 7.1</td>
<td>N/A</td>
<td>1,140 - 2,380</td>
<td></td>
</tr>
</tbody>
</table>

Consumer-grade sensors report concentrations in ppm$_v$. SI units are $\mu g$ m$^{-3}$. 1000 ppm$_v$ CO$_2$ = 929 $\mu g$ CO$_2$ m$^{-3}$ at 25 °C and 1 atm.

$^a$Classroom volume values from Ng et. al. 2020
https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=930986

$^b$Assuming outdoors 420 ppm
Using CO₂ as a Ventilation Clue

Fig. 1 Ventilation rate distribution (vertical line corresponds to ASHRAE recommended minimum)
Using CO$_2$ as a Ventilation Clue

**Mass Balance**

$\text{CO}_2 \text{ in room} = (\text{CO}_2 \text{ In}) - (\text{CO}_2 \text{ Out})$

*Assumes well-mixed room*
Using CO$_2$ as a Ventilation Clue
Using CO$_2$ as a Ventilation Clue

Data from student lab at Humboldt State University
Using CO$_2$ as a Ventilation Clue

\[ \ln \frac{(C_t - C_{outside})}{(C_{t=0} - C_{outside})} \text{ vs. } t \]

Complication #6

Data from student lab at Humboldt State University

Using CO$_2$ as a Ventilation Clue

Complication #7

Impacts of airtightening retrofits on ventilation rates and energy consumption in a manufactured home

Steven Nabinger, Andrew Persily

![Graph showing air change rate vs. wind speed](Image)
Using CO$_2$ as a Ventilation Clue

Complication #8
Using CO$_2$ as a Ventilation Clue

Complication #8
Using CO₂ as a Ventilation Clue

Complication #9

https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=930986
Using CO\textsubscript{2} as a Ventilation Clue

Effective Air Change Rate Estimation for Particle Removal

\[ \text{CO}_2 \text{ Measurement} + \text{Portable HEPA Filter} + \text{HVAC MERV 13 Filter} \]

Complication #10

Conclusion

Ventilation and Consumer Grade Cost Sensors:

*It’s complicated*