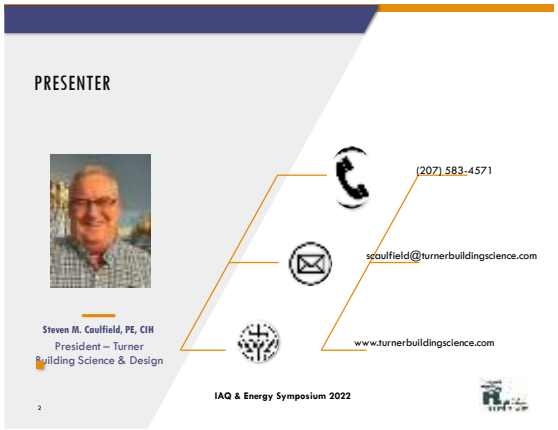


Background

CO_2 part of ventilation & IAQ discussions since 17th century

- Impacts on occupants
- Bioeffluent odor perception
- Ventilation rate estimation
- Ventilation control

Misinterpretation of CO_2 for years

More recently: more interest, more measurement, more confusion

CO_2 monitoring to manage ventilation

Long-term: Demand control ventilation

Short-term: Today's focus

Multiple purposes & approaches

- IAQ assessment
- Ventilation rate estimation
- Infection risk

Not always clear to user or receiver

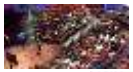
Long term indoor CO_2 monitoring demand control ventilation

Earliest references from 1970s

To avoid over- and under- per person ventilation rate

Required by building energy efficiency standards

Most relevant in spaces with unpredictable occupancy variations



Short-term CO_2 monitoring

IAQ Metric

Ventilation Rate

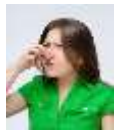
Infection Risk

Courtesy of David Meyer, Shenandoah University

ppm is not an SI unit.
µmol of CO_2/mol of air or µL/L are.
Using ppm_v today.

CO_2 as an IAQ metric

Maybe for contaminants related to # of occupants & activities but other important contaminants and sources



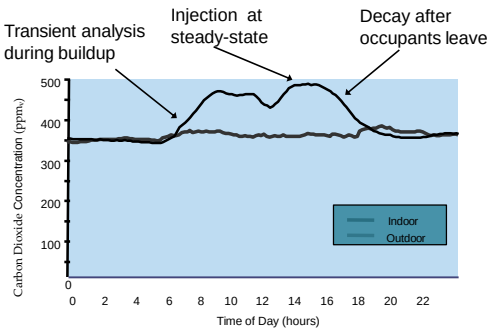
CO_2 to estimate ventilation rate

Tracer gas test methods:

ASTM E741 (D6245 for CO_2), ISO 12569

Decay, Constant injection, Constant concentration

Theory and assumptions; Single zone!!!



Persily, A.K. and Dols, W.S. (1990) The Relation of CO2 Concentration to Office Building Ventilation, *Air Change Rate and Airtightness in Buildings, ASTM STP 1067*, 77-92.

Using peak CO_2 to estimate per person outdoor ventilation rates

Single-zone constant injection tracer gas method

$$Q_{out} = \frac{G_{CO2}}{(C_{in,Steady-state} - C_{out})}$$

Assumptions: Single-zone, constant Q_{out}, G_{CO2} constant & known

CO_2 generation depends on activity, sex, age, body mass

Estimating before steady-state overestimates air change rate

Uncertainty calculations per ASTM D6245

Example calculation:
G_{CO2} = 0.0045 L/s; C_{ss} = 1000 ppm_v ; C_{out} = 400 ppm_v
Q_{out} = 7.5 L/s per person

CO_2 as an indicator of infection risk

To verify protective ventilation rate OR Indicator of risk

What is a protective ventilation rate?

Rebreathed air

Fate & transport of CO_2 ≠ F&T of virus-laden aerosol

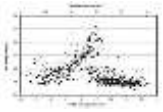
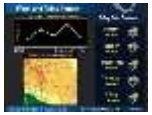
New studies and insights in real time

E.g., Kappelt, et al. 2021: "by measuring CO2 concentrations, only the number and volume concentrations of released particles can be estimated with reasonable certainty, while the number of suspended RNA copies cannot."

Thoughts on CO_2 monitoring

Variation happens
Occupancy, activities, ventilation system operation, weather

Measurement
Repeat; Calibration; Sampling location, duration and timing relative to occupancy; Compare to outdoors; Uncertainty; Repeat

Office building ventilation rate vs T_{out}

Thoughts on CO_2 monitoring

What value: Base on target OA/person or infection risk?
CDC: 800 ppm_v, "potential target benchmark for good ventilation"
REHVA: 800 ppm_v "indicator of good ventilation and IAQ."
UK SAGE: Spaces with high aerosol generation, < 800 ppm_v

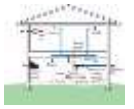
- Rationale for values???

ASHRAE, WHO & others recommend disabling DCV or reducing setpoint to ≈500 ppm

https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation.html
https://www.rehva.eu/fileadmin/user_upload/REHVA_COVID-19_guidance_document_V4.1_15042021.pdf
https://www.gov.uk/government/publications/emg-and-spi-b-application-of-co2-monitoring-as-an-approach-to-managing-ventilation-to-mitigate-sars-cov-2-transmission-27-may-2021

More thoughts on CO_2 monitoring

Make sure ventilation system is operating as intended
Outdoor air, filtration, controls, T & RH, …
Always been a good idea; more so now

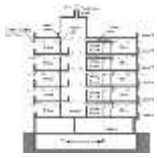



Using CO_2 monitoring
To estimate ventilation rate, OR
To prioritize for inspection & repair

Evaluating Ventilation Performance, Chapter in upcoming Handbook of Indoor Air Quality
Performance issues: System status, Envelope leakage, Ventilation system airflows, Outdoor air change rate, Interzone airflow, Air distribution
Building and system design information Outdoor air intake rate, controls, …

More thoughts on CO_2 monitoring

No OA ventilation system?
Natural ventilation or leakage only
Tracer gas methods challenging for natural ventilation

Example calculations

ASHRAE Standard 62.1 rates and default occupancies
Occupants (sex, age, mass, physical activity) to estimate CO_2 generation rate; Ceiling height; C_{out} = 400 ppm_v

Office space


Restaurant


Classroom


Auditorium


Example calculations

	Office	Classroom	Restaurant	Auditorium
Baseline ventilation parameters				
L/s per person	8.5	7.4	5.1	2.7
Air changes/h	0.5	2.2	3.2	1.9
Time to 95 % steady-state, h	5.9	1.4	0.9	1.5
Steady-state CO_2, ppm_v				
Baseline (Std 62.1)	999	1031	1533	2150
50 % occupancy	699	*749*	1028	1275
+50 % ventilation	*799*	*821*	*1156*	*1567*
10 L/s per person	909	867	976	873

On-line calculator

Https://pages.Nist.Gov/contam-apps/webapps/co2tool/#/

Search on: NIST CO2 tool

Summary

Ventilation important

But won't eliminate risk

Use a layered approach

When monitoring CO_2…

Measure and interpret with care

Measure more than once

Same reference value for all spaces?

More to evaluating ventilation than measuring CO_2

Report: Space & system types, design ventilation rate, occupant density, **time of measurement relative to occupancy,** outdoor concentration, **uncertainty**.

Reading list

In the works…

Revision of ASTM D6245-2018, Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation.

Persily, 2022?, Evaluating Ventilation Performance, Handbook of Indoor Air Quality, Springer Publishing https://link.springer.com/referencework/10.1007/978-981-10-5155-5

ASHRAE Position Document on Indoor CO_2

https://pages.nist.gov/CONTAM-apps/webapps/CO2Tool/#/

https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation.html

https://www.rehva.eu/fileadmin/user_upload/REHVA_COVID-19_guidance_document_V4.1_15042021.pdf

https://www.gov.uk/government/publications/emg-and-spi-b-application-of-co2-monitoring-as-an-approach-to-managing-ventilation-to-mitigate-sars-cov-2-transmission-27-may-2021

More reading

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ISO. 2017. Thermal performance of buildings and materials — Determination of specific airflow rate in buildings — Tracer gas dilution method, International Standards Organization.

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Kusuda, T. 1976. Control of Ventilation to Conserve Energy While Maintaining Acceptable Indoor Air Quality, *ASHRAE Transactions*, **82 (1)**, 1169-1181.

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Persily and de Jonge, 2017. Carbon Dioxide Generation Rates of Building Occupants, *Indoor Air*, **27**, 868-879.

Persily, 2018. Development of an Indoor Carbon Dioxide Metric, *39th AIVC Conference*, Antibes Juan-les-Pins, France, 791-800.

Persily and Polidoro. 2019. Residential Application of an Indoor Carbon Dioxide Metric, *40th AIVC Conference*, Ghent, Belgium, 995-1007.

Persily, 2021. Don't Blame Standard 62.1 for 1000 ppm CO_2, ASHRAE Journal, 63(2).

Wargocki, 2021. What we know and should know about ventilation, REHVA Journal, 58 (2).