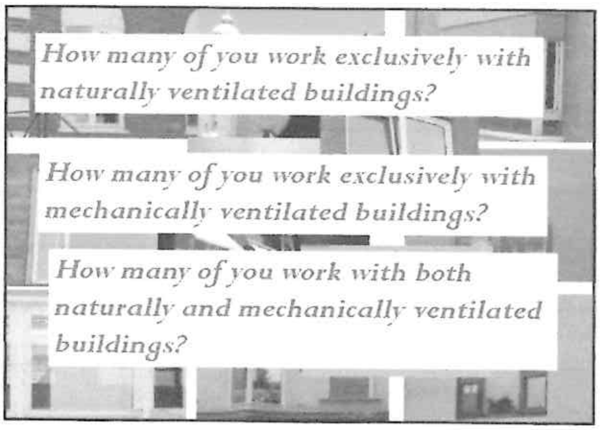
BUILDING DESIGN AND ENGINEERING APPROACHES
TO AIRBORNE INFECTION CONTROL
AUGUST 13, 2013 – Harvard School of Public Health

Natural Ventilation for Infection Control in Health Care Settings:

Theory

"In theory, there is no difference between theory and practice. But in practice, there is." - Yogi Berra

Hal Levin
Building Ecology Research Group
Santa Cruz, California
hlevin6@gmail.com



Natural Ventilation for Infection Control in Health Care Settings

Principles of ventilation and infection control (source: Nielsen, 2009)

Ventilation systems	Room air distribution system
Mechanical ventilation	Mixing ventilation
	Vertical ventilation
	Displacement ventilation
	Personalized ventilation
Natural ventilation	Mixing ventilation
	Displacement ventilation

Keys to Natural Ventilation for Infection Control in Healthcare Settings

- Air change rate
  - Ensure adequate average flow and minimum flow specifications are met
  - Approximate measurements under all weather and building operational conditions
  - Measurements, Verification
- Air distribution:
  - Flow direction:
    - Away from infected - verify
    - Ensure and verify consistency under all ventilation regimes
  - Flow of infectious agents directly out of building
  - Avoid flow toward other patients, especially susceptibles
- Management plan

Natural Ventilation: Theory Definitions

Purpose of ventilation: What is ventilation? Natural (Passive), Mechanical

Types of natural ventilation (Driving forces):
- Buoyancy (stack effect; thermal)
- Pressure driven (wind driven; differential pressure)

Applications
- Supply of outdoor air – removal of pollutants (e.g., infectious agents)
- Convective cooling
- Physiological cooling

Issues
- Weather-dependence: wind, temperature, humidity
- Thermal conditions, comfort/health
- Outdoor air quality/pollution
- Immune compromised patients
- Building configuration (plan, section)
- Management of openings
- Measurement and verification

What is ventilation?

Definitions covering ventilation and the flow of air into and out of a space include:

- **Purpose provided (intentional) ventilation:** Ventilation is the process by which 'clean' air (normally outdoor air) is intentionally provided to a space and stale air is removed. This may be accomplished by natural or mechanical means.
- **Air infiltration and exfiltration:** In addition to intentional ventilation, air inevitably enters a building by the process of 'air infiltration'. This is the uncontrolled flow of air into a space through adventitious or unintentional gaps and cracks in the building envelope. The corresponding loss of air from an enclosed space is termed 'exfiltration'.

Three elements of ventilation

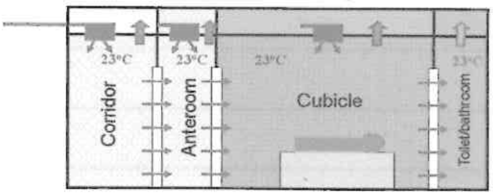
(source: Yuguo Li, personal communication)

Element	Description	Requirements/ Guideline	Design or Operation	Buildings	Cities
Primary	External air flow rate	Minimum ACH Minimum L/s-p	Fan, duct, openings or streets	ASHRAE 62 1-12 ACH	?
Secondary	Overall flow direction between zones	Flow clean to "dirty" spaces	Pressure control through airflow imbalance Prevailing winds	Positive/ negative 2.5-15 Pa isolation/ smoke control	Dirty industry downwind Buy upwind
Tertiary	Air distribution within a space	Ventilation effectiveness, no short-circuiting	Use of CFD Smoke visualization	Ventilation strategies	Urban planning

Isolation room ventilation

Goal: ~12 ach or 160 l/s-p (?)

Suspended ceilings



The purpose is Not to have a 2.5 Pa negative pressure, but no air leaks to the corridor!

Recommended negative pressure is ~ 10 Pa with wind, ~2.5 Pa without wind

Courtesy of Yuguo Li

Space vol = floor area x height

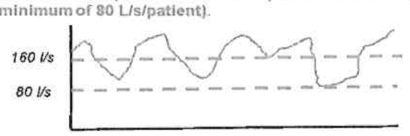
NatVent for healthcare

- Intake/reception areas
  - Administrative measures, Triage potential cases: "Have you been coughing for the past 20 days? If so, go over there."
- General areas
  - Ensure at least 2 air changes per hour (ACH, or h^{-1} or 1/h)
  - Patient rooms: Ensure ≥2 ACH, one-pass, no recirculation
- Isolation rooms/wards
  - Ensure 6 ACH, design and operate for 12 ACH, 160 L/s-p
  - Vent to outside; Ideally a free-standing structure or unconnected directly to other areas
- Procedure rooms
  - Always ventilated to outside, Free-standing if possible

WHO 2009 NatVent Guideline – key ideas

Courtesy of Yuguo Li

- For natural ventilation, a minimum hourly averaged ventilation rate of 160 L/s/patient for airborne precaution rooms (with a minimum of 80 L/s/patient).



- When natural ventilation alone cannot satisfy the requirements, mechanically assisted natural ventilation system should be used.
- Overall airflow should bring the air from the agent sources to areas where there is sufficient dilution, and preferably to the outdoors.

HB2009 Seven conjectures

(source: Yuguo Li, HB2009, Syracuse, Sept 2009)

1. *Ventilation can reduce infection risk in a room.*
2. *Airflow can transport infection risk from one location to another.*
3. *Airflow can reduce infection risk at source.*
4. *Infection risk quickly reduces as moving away from the source in fully mixing ventilated rooms.*
5. *There exists a certain ventilation rate value below which the overall infection risk is more significant than that at no ventilation.*
6. *There exists a certain ventilation rate above which the reduction of overall infection risk is insignificant as compared to other control methods.*
7. *There exists a certain ventilation rate above which the overall infection risk is absent.*

Types of natural ventilation

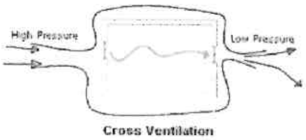
Stack effect (buoyancy)

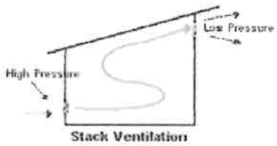
- Warm air is lighter (less dense) than cold air
- Warm air rises, cold air falls
- Intentional chimneys (stacks) can create larger differences between top and bottom, increasing the air flow rate

Wind-driven (pressure)

- Pressure differences result in air mass movement
- "Packets" of air flow from higher to lower air pressure regimes

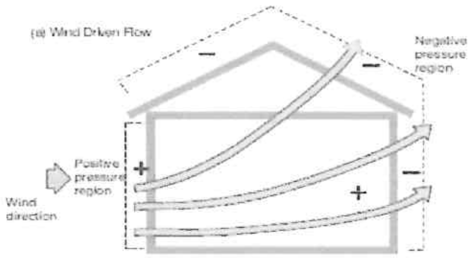
Wind driven vs. Stack effect





Natural Driving Mechanisms – Pressure: Wind-driven air flow

Natural Driving Mechanisms – Pressure: Wind-driven air flow



Wind Pressure as a function of angle of incidence on wall

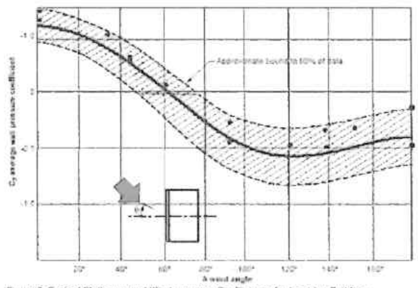
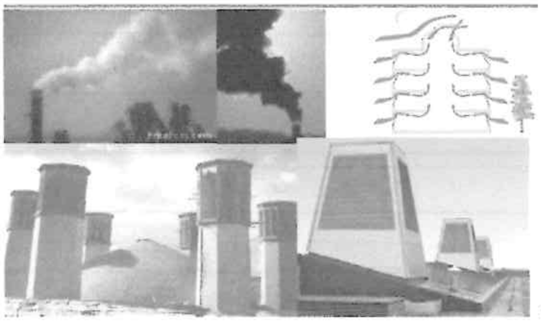
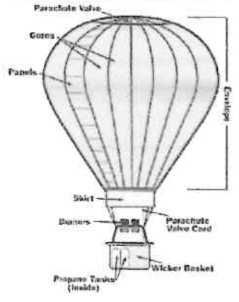


Figure 3. Typical Wall-averaged Wind pressure Coefficients for Low-rise Buildings

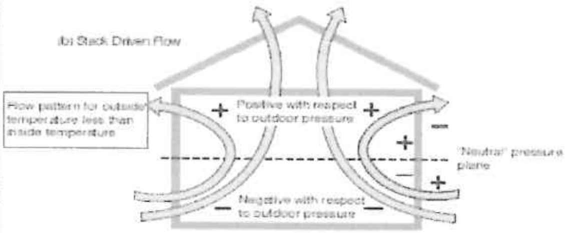
Natural driving mechanisms -- Buoyancy Stack effect



Hot air ➡ buoyancy



Natural driving mechanisms -- Buoyancy Stack effect

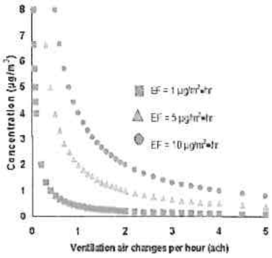


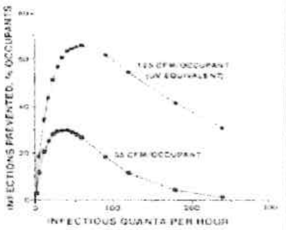
Applications of Natural ventilation: Supply of outdoor air

- Supply of outdoor air … removal of pollutants
  - In air changes per hour (AER or h^{-1}) or liters per second per person (l/s-p)
  - What happens if you have a very tall space? AER vs l/s-p?
- Pollutant concentration = source emission ÷ removal rate
  - Removal rate includes dilution/exhaust plus deposition on surfaces or chemical interactions/transformation
  - Chemicals or particles: source strength expressed as mg of pollutant / m^2-h or mg/h
  - Dilution/exhaust rate expressed as dilution ventilation (air changes per hour, ach, AER, h^{-1})
  - Removal rate ("Deposition velocity"; g $cm^{-1}s^{-1}$)

DILUTION

Pollutant concentration as a function of outdoor air exchange rate

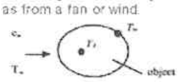




Nardell, 1991 *Amer Rev Resp Disease*

Applications of Natural Ventilation: Convective cooling

- **convection** /con·vec·tion/ (kon-vek´shun) the act of conveying or transmission, specifically transmission of heat in a liquid or gas by bulk movement of heated particles to a cooler area.
- Air flow around a person can be caused by the higher temperature of the person's skin relative to the air around it, giving rise to an air flow known as the "thermal plume," air movement predominantly in an upward direction.
- Or, it may be caused by forced air movement, as from a fan or wind.



Temperature variation in an object cooled by a flowing liquid

Convective cooling: examples

Physiological cooling

Physiological cooling

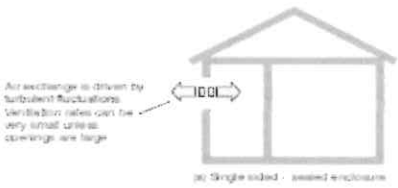
Applications: Physiological cooling

"Ectothermic cooling"

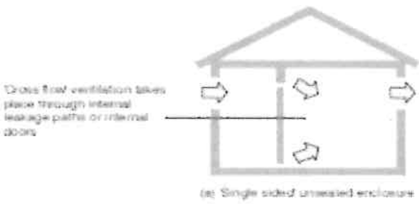
- Vaporization:
  - Getting wet in a river, lake or sea.
- Convection:
  - Entering a cold water or air current.
  - Building a structure that allows natural or generated air flow for cooling.
- Conduction:
  - Lie on cold ground.
  - Staying wet in a river, lake or sea.
  - Covering in cool mud.
- Radiation:
  - Find shade.
  - Enter a cave or hole in the ground shaped for radiating heat (Black box effect).
  - Expand folds of skin.
  - Expose skin surfaces.

Convective + Physiological cooling

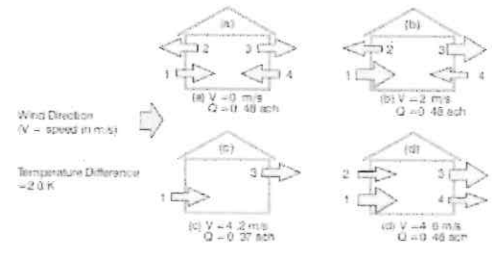
Single-sided ventilation



Cross-flow ventilation



Influence of wind and temperature (stack effect) on ventilation and air flow pattern

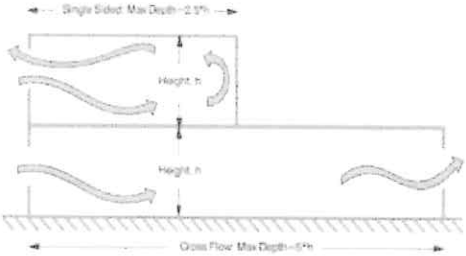


Influence of wind and temperature (stack effect) on ventilation rate and air flow pattern

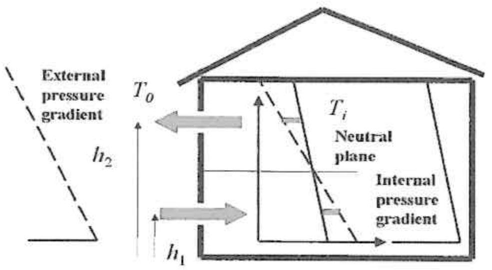
(source: AIVC, 2009)

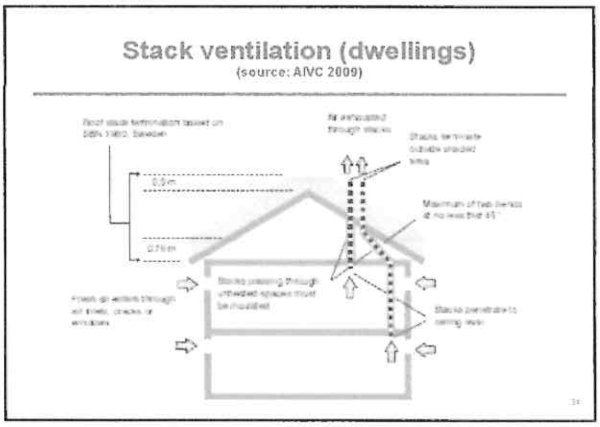
Single-sided vs. Cross flow ventilation

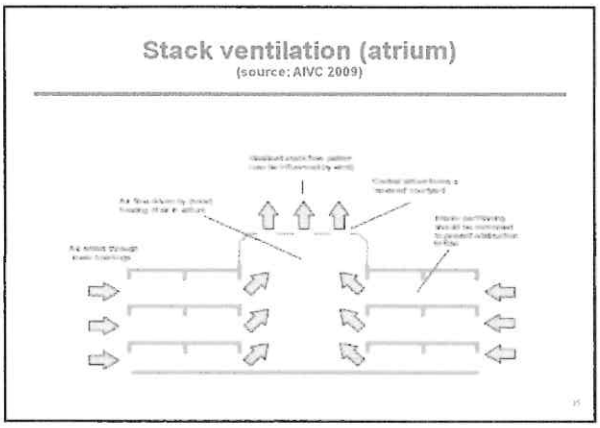
(source: AIVC, 2009)

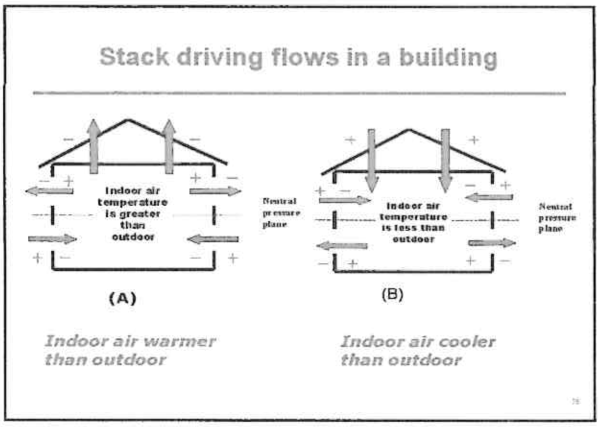


Concept of the "neutral" level: pressure or buoyancy-driven ventilation




Stack ventilation (dwellings)
(source: AIVC 2009)


Stack ventilation (atrium)
(source: AIVC 2009)


Stack driving flows in a building
Indoor air temperature is greater than outdoor
Neutral pressure plane
Indoor air temperature is less than outdoor
Neutral pressure plane
(A)
(B)
Indoor air warmer than outdoor
Indoor air cooler than outdoor

Natural ventilation in buildings

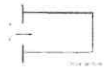
By Francis Allard, Mat Santamouris, Servando Alvarez, European Commission. Directorate-General for Energy, ALTENER Program

Table 1.1. Formulae for single-sided ventilation [1]

(a) Ventilation due to wind

$Q = 0.025AV$

where A is the opening surface and V is the wind velocity.

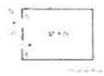


(b) Ventilation due to temperature difference with two openings

$$Q = C_d A \left[\frac{\varepsilon\sqrt{2}}{(1+\varepsilon)(1+\varepsilon^2)^{1/2}}\right]\left(\frac{\Delta T g H_1}{T}\right)^{1/2}$$

$\varepsilon = A1/A2,\ A = A1 + A2$

where C_d is the discharge coefficient



(c) Ventilation due to temperature difference with one opening

$$Q = C_d \frac{A}{3}\sqrt{\frac{\Delta T g H}{T}}$$

http://books.google.com/books?hl=en&lr=&id=1tdOMyhPA2gC&oi=fnd&pg=PR9&dq=Natural+ventilation+theory&ots=mFzmfd4mct&sig=XA3zksH_OBkkS8tlLbxmwJgbWyo

Natural ventilation in buildings

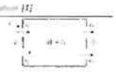
Francis Allard, Mat Santamouris, Servando Alvarez, European Commission. Directorate-General for Energy, ALTENER Program

Table 1.2. Formulae for cross ventilation [1]

(a) Ventilation due to wind only:

$$Q_w = C_d A_w V \sqrt{\Delta C_p}$$

$$\frac{1}{A_w^2} = \frac{1}{(A_1 + A_2)^2} + \frac{1}{(A_3 + A_4)^2}$$



(b) Ventilation due to temperature difference only:

$$Q_b = C_d A_b \left(\frac{2\Delta T g H_1}{T}\right)^{1/2}$$

$$\frac{1}{A_b^2} = \frac{1}{(A_1 + A_3)^2} + \frac{1}{(A_2 + A_4)^2}$$

$$T = \frac{T_i + T_e}{2}$$

(c) Ventilation due to wind and temperature difference:

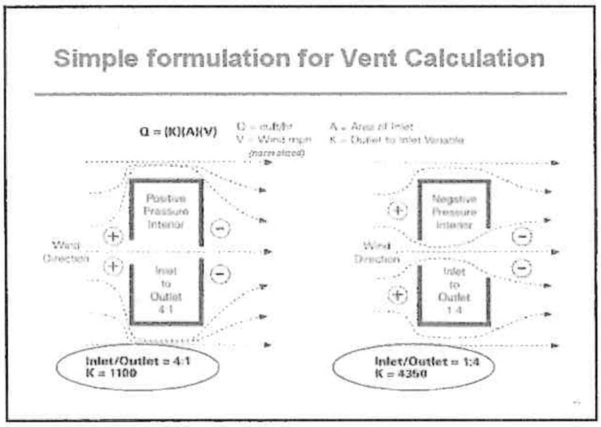
$$Q = Q_b \text{ for } \frac{V}{\sqrt{\Delta T}} < 0.26\sqrt{\frac{A_b}{A_w}}\sqrt{\frac{H_1}{\Delta C_p}}$$

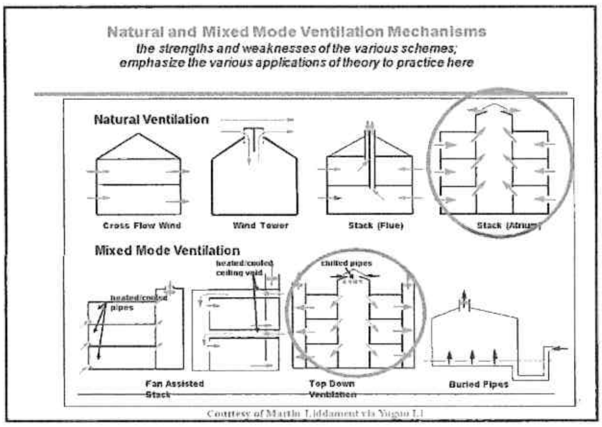
$$Q = Q_w \text{ for } \frac{V}{\sqrt{\Delta T}} > 0.26\sqrt{\frac{A_b}{A_w}}\sqrt{\frac{H_1}{\Delta C_p}}$$

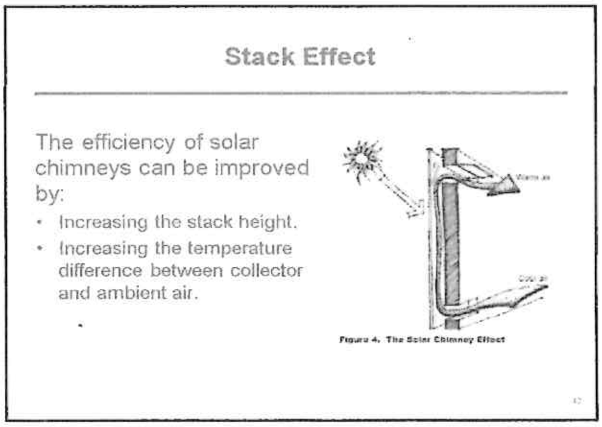
$\Delta T = T_i - T_e$

Indoor air velocities for naturally ventilated spaces under different wind directions and different number of apertures and locations (Allard et al)

Conditions	Width of aperture/width of wall = 0.66 V_{av} (%)	Width of aperture/width of wall = 0.66 V_{max} (%)	Width of aperture/width of wall = 1 V_{av} (%)	Width of aperture/width of wall = 1 V_{max} (%)
Single aperture in windward wall, wind direction perpendicular	13	18	16	20
Single aperture in windward wall, wind direction at an angle	15	33	23	36
Single aperture in leeward wall, wind direction at an angle	17	44	17	39
Two apertures in leeward wall, wind direction at an angle	22	56	23	50
One aperture in windward wall, another in adjacent wall, wind direction perpendicular to inlets	45	68	51	103
One aperture in windward wall, another in adjacent wall, wind direction at an angle	37	118	40	110
One aperture in windward wall, another in leeward wall, wind direction perpendicular to inlet	35	65	37	102
One aperture in windward wall, another in leeward wall, wind direction at an angle	42	83	42	94

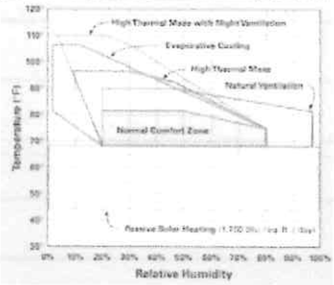

Simple formulation for Vent Calculation
Q = (K)(A)(V)
Q = cuft/hr
V = Wind mph
(normalized)
A = Area of Inlet
K = Outlet to Inlet Variable
Wind Direction
Positive Pressure Interior
Inlet to Outlet 4:1
Inlet/Outlet = 4:1
K = 1100
Negative Pressure Interior
Inlet to Outlet 1:4
Inlet/Outlet = 1:4
K = 4350


Natural and Mixed Mode Ventilation Mechanisms
the strengths and weaknesses of the various schemes;
emphasize the various applications of theory to practice here
Natural Ventilation
Cross Flow Wind
Wind Tower
Stack (Flue)
Stack (Atrium)
Mixed Mode Ventilation
heated/cooled pipes
heated/cooled ceiling void
chilled pipes
Fan Assisted Stack
Top Down Ventilation
Buried Pipes
Courtesy of Martin Liddament via Yuguo Li


Stack Effect
The efficiency of solar chimneys can be improved by:
• Increasing the stack height.
• Increasing the temperature difference between collector and ambient air.
Figure 4. The Solar Chimney Effect

Design strategies for Natural Ventilation as a thermal control strategy

- *Overall building design strategy must match the climate conditions and the need for high outdoor air ventilation rates*
- *Natural ventilation can work in outdoor Temperature range from 40 F (5 C) up to 110 F (43 C), but Relative Humidity is a critical factor*



Natural Ventilation Issues

- Weather-dependence: wind, temperature, humidity
- Thermal conditions: comfort, health
- Outdoor air quality/pollutants
- Immune compromised patients
- Building configuration (plan, section)
- Management of openings
- Measurement of ventilation rate(s)

How to use natural ventilation to cool narrow office buildings

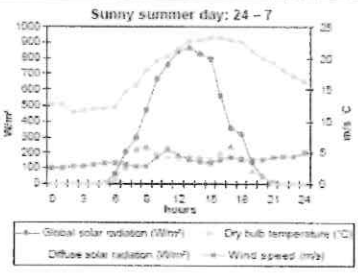
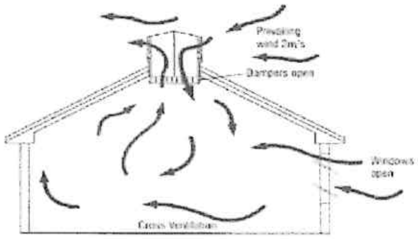


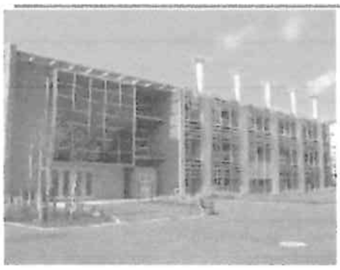
Fig. 7 Climatic data of the sunny summer day

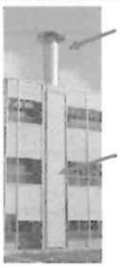
Windcatcher ventilation



Wind Tower Ventilation

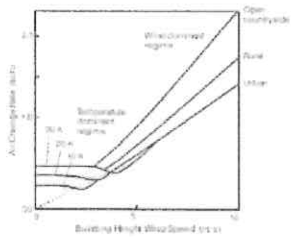
BRE's Environmental Office Building





- *Low energy fans for use on still air days*
- *Glass for solar heating of thermal chimney*

Impact of wind and temperature difference on natural ventilation



Natural ventilation in buildings

Francis Allard, Mat Santamouris, Servando Alvarez, European Commission. Directorate-General for Energy, ALTENER Program

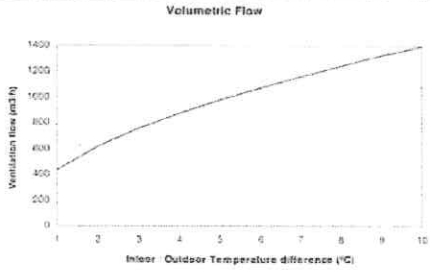
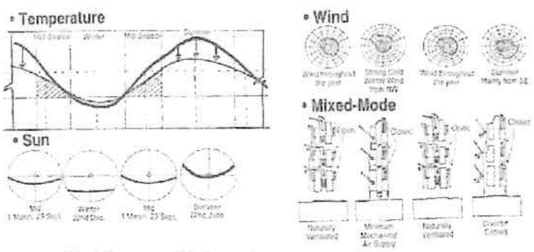


Figure 2.33. Airflow as a function of the temperature difference

Weather conditions and ventilation mode

Armoury Tower – Shanghai, China



***Wind Towers*, 1999. Battle McCarthy Consulting Engineers**

Climate Typology (oversimplified!) What is your climate type?

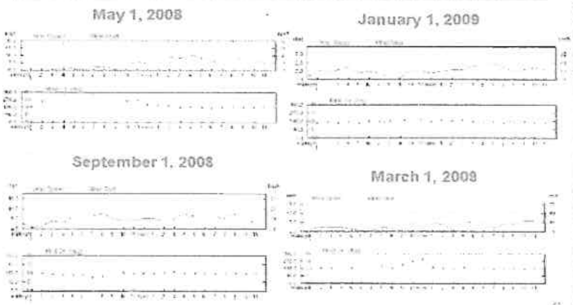
Climate type	*Diurnal swing*	*Steady daily cycle*	*Seasonal variation*	*No seasonal variation*
Hot humid		Singapore		
Hot dry	Low desert	Las Vegas	Albuquerque	
Temperate humid		London	Milan, Italy	
Temperate dry	High desert			Quito, Ecuador
Temperate seasonal – Temp	Boston	Lima, Peru	Montreal, Capetown, Melbourne	
Temperate seasonal – RH	San Francisco Mt. Fuji			
Cold humid	Anchorage			
Cold dry	Bogotá			Bogotá

Wind: direction and velocity are neither stable nor consistent – almost anywhere

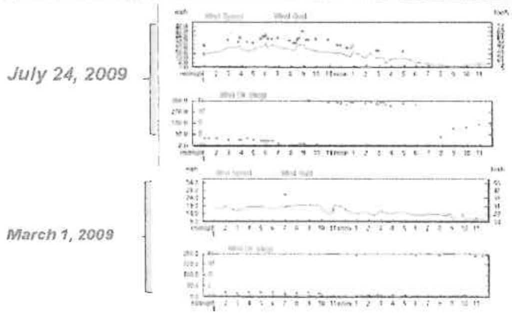
- Selected data from almost any city will show daily cycles and variations in wind direction and velocity
- Seasonal variations are more reliable, but daily variations are still the rule rather than the exception
- Even with many predictable situations, wind direction will change over the diurnal cycle – California coast is an example.
- Local wind can be very place-specific, even within a city or a countryside location.
- Relying on wind alone can result in both under and over-ventilation relative to a design objective.

Weather – "wait a minute and it will change"

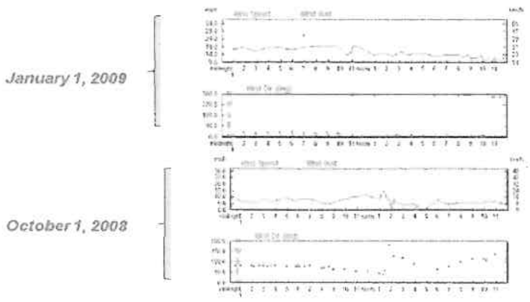
Lima, Peru: wind speed and direction



Boston, MA

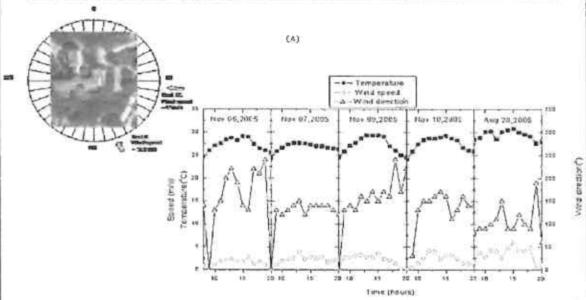


Boston, MA



Grantham Hospital Study, Hong Kong

Yuguo Li, WHO 2009



Outdoor air quality becomes indoor air quality at high ventilation rates

- The higher the outdoor air ventilation rate, the higher the indoor/outdoor pollutant concentration
- The effect of the building on reducing outdoor pollutants varies by pollutant and by building ventilation pathways
- Where outdoor air pollution is high, natural ventilation must be considered not only as a means for reducing concentrations from indoor sources (infectious airborne agents as well as chemicals emitted indoors), but also as a means of delivering un-cleaned outdoor air.
- With highly susceptible health care facility occupant populations, consideration must be given to the effects of outdoor pollutants on the occupants' health.

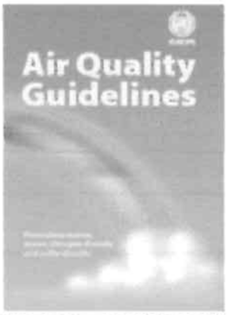
Air Quality Guidelines: Global Update WHO, 2005

Chapter 2.

Global ambient air pollution concentrations and trends

Bjarne Sivertsen

http://www.who.int/phe/health_topics/outdoorair_aqg/en/



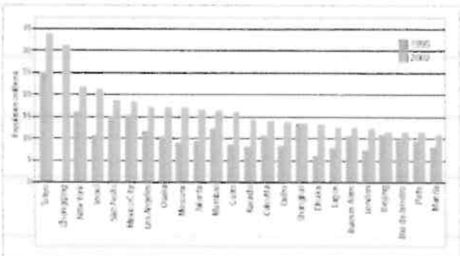
Ranges of annual average concentrations of outdoor air pollutants by continent based on selected urban data

Region	PM_{10}	Nitrogen dioxide	Sulfur dioxide	Ozone (1-hour maximum concentration)
Africa	40–150	35–65	10–100	120–300
Asia	35–220	20–75	6–65	100–250
Australia/New Zealand	28–127	11–28	3–17	120–310
Canada/United States	20–60	35–70	9–35	150–380
Europe	20–70	18–57	8–36	150–350
Latin America	30–129	30–82	40–70	200–600

(source: World Health Organization, 2005. *Air Quality Guidelines: Global Update*)

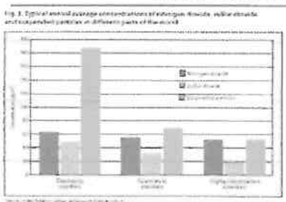
Where are the people who will arrive in naturally-ventilated health care facilities?

Fig. 2. The 24 megacities in the world with populations (including suburbs) exceeding 10 million in 2002



(source: World Health Organization, 2005.

Pollutant concentrations by national level of development: increased development can mean more motor vehicle combustion



(source: World Health Organization, 2005.

Shanghai, January 2013

U.S. EPA National Ambient Air Quality Standards (NAAQS) http://www.epa.gov/air/criteria.html

	Primary Standards		Secondary Standards	
Pollutant	Level	Averaging Time	Level	Averaging Time
Carbon Monoxide	9 ppm ($10\ mg/m^3$)	8-hour	None	
	35 ppm ($40\ mg/m^3$)	1-hour		
Lead	$0.15\ \mu g/m^3$	Rolling 3-Month Average	Same as Primary	
	$1.5\ \mu g/m^3$	Quarterly Average	Same as Primary	
Nitrogen Dioxide	0.053 ppm ($100\ \mu g/m^3$)	Annual (Arithmetic Mean)	Same as Primary	
→ Particulate Matter (PM_{10})	$150\ \mu g/m^3$	24-hour	Same as Primary	
Particulate Matter ($PM_{2.5}$)	$15.0\ \mu g/m^3$	Annual (Arithmetic Mean)	Same as Primary	
	$35\ \mu g/m^3$	24-hour	Same as Primary	
Ozone	0.075 ppm (2008 std)	8-hour	Same as Primary	
	0.08 ppm (1997 std)	8-hour	Same as Primary	
	0.12 ppm	1-hour	Same as Primary	
Sulfur Dioxide	0.03 ppm	Annual (Arithmetic Mean)	0.5 ppm ($1300\ \mu g/m^3$)	3-hour
	0.14 ppm	24-hour		

Estimated annual average PM_{10} concentrations in cities with populations >100,000 and in national capitals

Source: Map provided by Kiran Dev Pandey, World Bank.

U.S. EPA National Ambient Air Quality Standards (NAAQS) http://www.epa.gov/air/criteria.html

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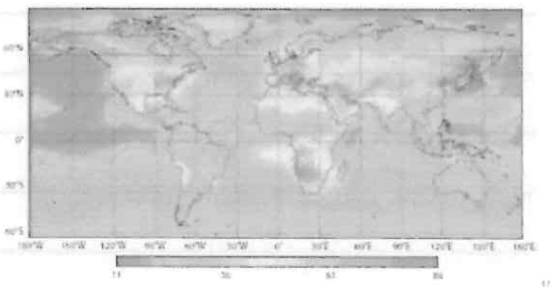
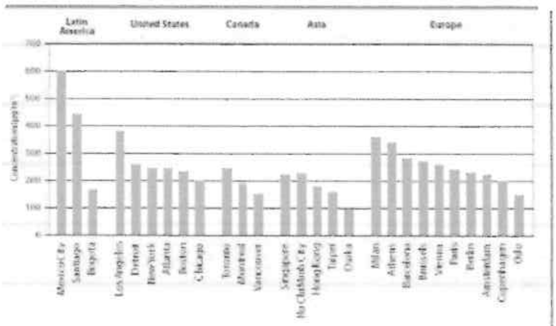
	0.14 ppm	24-hour		

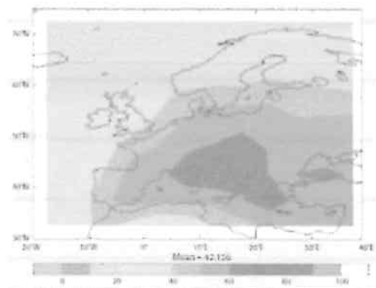
Mean afternoon (13:00 to 16:00) surface ozone concentrations calculated for the month of July (comment: where are people living?)



Highest (1-hour average) ground-level ozone concentrations measured in selected cities



Modeled surface ozone concentrations (ppb) over Europe during July for the years 2000– 2009



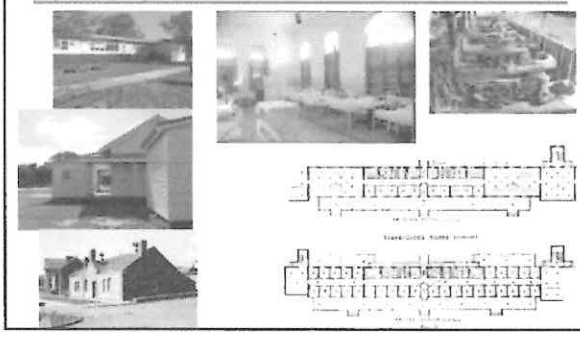
Indoor O_3 concentration as a function of outdoor concentration and ventilation rate

AER (h^{-1})	Outdoor Air Ozone Concentration (parts per billion)									
	20	40	60	80	100	120	140	160	180	200
1	5	10	15	20	25	30	35	40	45	50
2	7	15	22	30	37	45	52	60	67	75
4	11	22	33	44	55	66	77	88	99	110
6	13	26	40	53	66	79	92	106	119	132
12	16	32	48	64	80	96	112	128	144	160
20	18	36	54	72	90	108	126	144	162	180

Immune compromised patients

- What is the trade-off between reducing the risk of infection by unfiltered outdoor air ventilation and decreasing the airborne concentration of infectious airborne agents?
- Does it depend on the kind and level of pollution?
- Does it depend on the kind of level of infectious agent?
- Does it depend on the health status of the patient?
- Does it depend on the age and life expectancy of the patient?
- Is there a simple answer to this dilemma?

Building configuration



Management of openings

- Who's in charge here?
- What if the weather is bad?
- What if it's smoky outside?
- Security?

Measurement issues

- How do you confirm adequate outdoor air ventilation in a naturally-ventilated healthcare facility?
- Methods for approximation available, precise numbers are not feasible …. Nor necessary.
- Carbon dioxide from occupants simply not technically valid for high air change rates – 6 to 12 ach.
- Only under special conditions can CO_2 be used in lower occupant density spaces – steady conditions, not usually present for natural ventilation.
- Air flow direction can be and should be confirmed.
- Empty space vent rate can be characterized reasonably well by carbon dioxide (or other tracer gas) decay rate.

Natural Ventilation: Theory Summary - Review

Purpose of ventilation What is ventilation?

Types of natural ventilation (Driving forces):

- Buoyancy (stack effect; thermal)
- Pressure driven (wind driven; differential pressure)

Applications

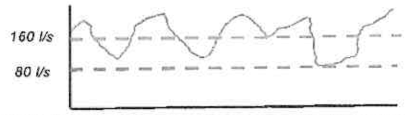
- Supply of outdoor air
- Convective cooling
- Physiological cooling

Issues

- Weather-dependence: wind, temperature, humidity
- Outdoor air quality
- Immune compromised patients
- Building configuration (plan, section)
- Management of openings
- Measurement and verification

WHO 2009 NatVent Guideline – key ideas
(source: Y. Li, HB2009, Syracuse.)

- For natural ventilation, a minimum hourly averaged ventilation rate of 160 L/s/patient for airborne precaution rooms (with a minimum of 80 L/s/patient).



- When natural ventilation alone cannot satisfy the requirements, mechanically assisted natural ventilation system should be used.
- Overall airflow should bring the air from the agent sources to areas where there is sufficient dilution, and preferably to the outdoors.

cl 60

Keys to Natural Ventilation for Infection Control in Healthcare Settings

- Air change rate
  - Ensure adequate average flow and minimum flow specifications are met
  - Approximate measurements under all weather and building operational conditions
  - Measurements, Verification
- Air distribution:
  - Flow direction:
    - Away from infected - verify
    - Ensure and verify consistency under all ventilation regimes
  - Flow of infectious agents directly out of building
  - Avoid flow toward other patients, especially susceptibles
- Management plan

Natural Ventilation: Theory References

Allard, Francis, Mat Santamouris, Servando Alvarez. "Natural ventilation in buildings." European Commission, Directorate-General for Energy, ALTENER Program. on-line: [illegible]

Andersen, Karl Terpager. 2003. Theory for natural ventilation by thermal buoyancy in one zone with uniform temperature. *Building and Environment* **38**. 1281–1289.

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Nielsen, P. V. 2009. Control of airborne infectious diseases in ventilated spaces. *J. R. Soc. Interface* 2009 6, S747-S755. available at http://rsif.royalsocietypublishing.org/

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WHO, 2009. Natural Ventilation for Infection Control in Health-Care Settings. Geneva: World Health Organization. http://www.who.int/water_sanitation_health/publications/natural_ventilation.pdf

Natural Ventilation: Measurement Challenges

Hal Levin
Building Ecology Research Group
Santa Cruz, California USA
hlevin6@gmail.com

Building Design and Engineering Approaches to Airborne Infection Control
Harvard School of Public Health – August 2, 2012

Steady State (*theoretical*) basis for fully mixed room

$$C(t) - Co = S\,(1 - e^{-at}) / aV$$

where
c(t) = indoor concentration (volumetric proportion) at time t,
Co = constant outdoor concentration (volumetric proportion),
S = generation rate of the source (volume per time unit),
a = air change rate (per time unit),
t = time, and
V = volume in the occupied space.

Requirements for satisfying quasi steady state conditions during build-up period

- Constant number of occupants
- Constant occupant metabolic rate
- Constant outdoor air CO_2 concentration
- Constant ventilation rate (mechanical, leakage, and entry from adjacent (connecting) spaces all at same conditions of occupancy and ventilation
- Are these conditions ever met in your experience?

CO_2 is easy to measure, right?

It is easy to calculate or assess ventilation based on CO_2 measurements, right?

- $C(t) - Co = S(1 - e\text{-}at)/aV$

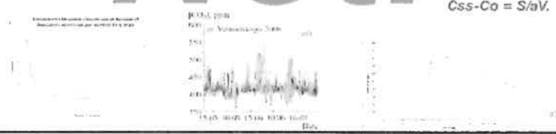
At=	Percent Steady State	Hours required at alternative ACH				
		ACH 0.25	ACH=0.5	ACH=.75	ACH=1.0	ACH=2.0
1	63.21%	4	[illegible]	1.33	1	0.5
2	86.47%	8	[illegible]	2.67	2	1
3	95.02%	12	[illegible]	4	3	[illegible]
4	98.17%	16	[illegible]	5.[illegible]	4	[illegible]
5	99.33%	20	10	[illegible]	[illegible]	2.5

$Css - Co = s/$[illegible]

Steady State Ind-Out CO_2 (ppm)	Outdoor Air (cfm/p)	Outdoor air (L/s-p)
4700	2	1
[illegible]	5	2
[illegible]	6	3
[illegible]	9	4
[illegible]00	15	7
[illegible]00	18	8
[illegible]00	21	10

$Css - Co = S/aV.$

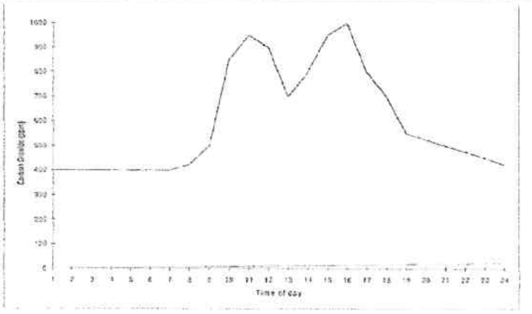
Not!



Basic theory of CO_2-ventilation relationships

- Typical CO_2 concentration in relation to occupancy
- Steady State theoretical basis
- Indoor and outdoor sources of CO_2
- Indoor – Outdoor (I-O) CO_2 relationships
- Variations in occupant generation rates- metabolism as a function of activity, gender, age, health status
- Steady state construct and reality in real world buildings
- Variable outdoor air concentrations

Lag time: Typical CO_2 concentration in relation to typical office building occupancy



Indoor and outdoor sources of CO_2

OUTDOOR CO_2

- CO_2 outdoor sources dominated by combustion processes
- CO_2 outdoors is removed by plants – concentrations in a forest can be 10s of ppm below global ave. concentrations
- Global average ~400 ppm rising approximately 3 ppm/year
- Urban concentrations can be ~50 to 400 ppm higher than global average concentrations (425 – 600 ppm)

INDOOR CO_2

- People, animals exhale concentrations of 20 to 40 * 10^3 ppm
- Combustion processes (cooking, water heaters, space heaters, fires)
- Plants absorb a little indoor air CO_2

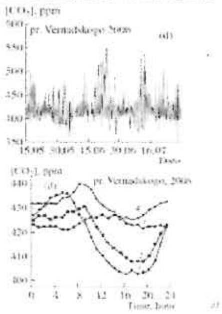
Variable outdoor air concentrations 390-600 ppmv today!

TIME DEPENDENCY

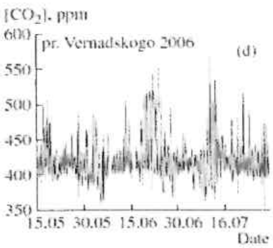
- Daily – traffic, power plants, process combustion
- Weekly – commuters, recreation
- Seasonal – plant growth, foliage; temperature, humidity, wind

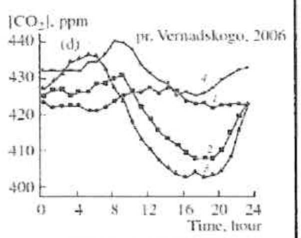
LOCATION DEPENDENCY

- Near power plants, other strong point sources
- Near roadways, parking lots
- Population density (urban-rural), building-roadway ratios
- Height above the ground
- Near dense forests (even urban)



Time-, day-, and Season-dependent variation in outdoor CO_2

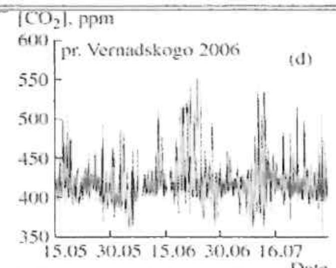




(1) winter, (2) spring, (3) summer, and (4) fall.

"Typical" CO_2 concentrations in urban air?

(Gorchakov et al, 2008, Izvestiya AN. Fizika Atmosfery i Okeana, 2009, Vol. 45, No. 3, pp. 237–347)

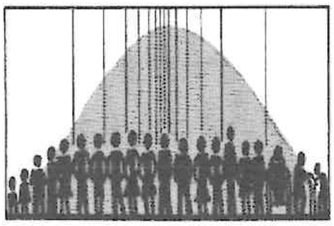


It is evident from Fig. 1 that these concentrations vary widely and that the diurnal cycle and intradiurnal variability of concentrations are important for all of the gaseous components considered here. In particular, the range of intradiurnal variations of carbon dioxide concentration reaches 150 ppm with a noise component near ±5 ppm.

Variations in occupant generation rates-

METABOLISM AS A FUNCTION OF...

- Activity level (metabolic rate)
- Diet (metabolic rate)
- Gender (?)
- Age (size?)
- Health status
- Stress (Wang, 1971, *ASHRAE Transactions*)



Steady state construct (theory) and real world buildings

In summary

"Everything changes"

- Suzuki Roshi
(contemporary Zen master)

Issues: use of CO_2 measurement devices

- Requirements for satisfying quasi steady state conditions
- Accuracy and stability of sensors
- Calibration issues
- Portable vs. fixed monitors
- Multiple vs single sensor measurements
- Lag time, short time periods of activity, intermittent occupancy
- Special issue of high density occupancy
- Variability among measurement devices
- Use of CO_2 for Demand Controlled Ventilation (DCV)
- Approaches to correcting for problems

Accuracy of CO_2 Sensors in Commercial Buildings: A Pilot Study

Fisk, Faulkner, and Sullivan, 2006, LBNL Report 61862

Many anecdotal reports of poor CO_2 sensor performance in actual commercial building applications.

Evaluated the accuracy of 44 CO_2 sensors located in nine commercial buildings to determine if CO_2 sensor performance, in practice, is generally acceptable or problematic.

CO_2 measurement errors varied widely, sometimes hundreds of ppm.

Despite its small size, study indicates accuracy of CO_2 sensors used in commercial buildings frequently less than needed to measure peak indoor-outdoor CO_2 concentration differences with less than a 20% error.

Conclusion: there is a need for more accurate CO_2 sensors and/or better sensor maintenance or calibration procedures.

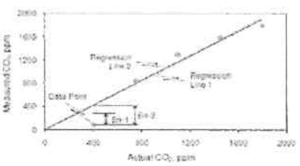
Accuracy and stability of sensors

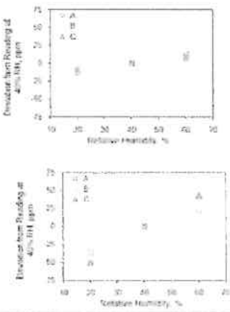
Shrestha et al, 2009. An Experimental Evaluation of HVAC Grade Carbon-Dioxide Sensors: Part 2, Performance Test Results

- Fifteen models of NDIR HVAC-grade CO_2 sensors were tested and evaluated to determine the accuracy, linearity, repeatability, and hysteresis of each sensor.
- The sensors were tested at 40% relative humidity, 73°F (22.8°C) temperature, 14.70 psia (101.35 kPa) pressure, and at five different CO_2 concentrations (400 ppm, 750 ppm, 1100 ppm, 1450 ppm, and 1800 ppm).
- The test results showed a wide variation in sensor performance among the various manufacturers and in some cases a wide variation among sensors of the same model.

Accuracy and stability of sensors

Shrestha, *ASHRAE Transactions, Pt.1*, 2010





***None** of the tested transmitter manufacturers reported humidity sensitivity*

Calibration issues

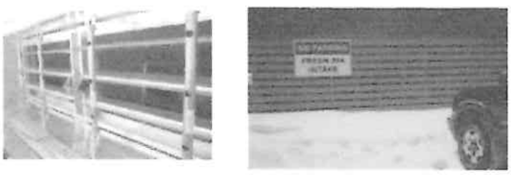
- Portable handheld monitors are known to lose calibration Easily and must be re-calibrated frequently, perhaps daily, perhaps after any significant move or time has elapsed.
- The need for calibration makes the use of the portable, handheld devices as well as sensors used for DCV far less convenient and useful.

Where to measure ventilation or air flow?

Ventilation- air flow measurement

Air capture hood for air flow measurement

Where to measure air flow?



Where to measure air flow?

What to measure?

CO_2 *Air flow rate* *ventilation rate* *air flow direction*

Interpretation of "Results"

- How do we interpret results?
- What does 215 ACH really mean? How do we know the range.
- Is it good to have a lot of ACH part of the day and little the another part?
- Should we simply say poor, OK, and great (or a lot)?