Energy Efficiency and Indoor Air Quality with Demand Controlled Ventilation

Carbon Dioxide Measurements for HVAC

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Topics

The Application
The Benefits
The Challenges
The Technology
The Service
Vaisala In Brief

- We serve customers in Weather and Controlled Environment markets
- 80+ years of experience providing a comprehensive range of innovative observation and measurement products and services
- Trusted supplier of instrumentation to protect sensitive areas and explore the unknown
- Various measuring and monitoring solutions developed for indoor and industrial environments ensure, product quality, cost/energy efficiency and personal safety and wellbeing
The DCV Application
Demand Controlled Ventilation

- **Definition** – A ventilation system control strategy that provides for the automatic reduction of outdoor air intake below design rates when the actual occupancy of spaces served by the system is different than the design occupancy.

- Every building and room has variable occupancy rates, which creates a variable need for ventilation.

- DCV presents opportunity for energy savings with varied ventilation rates
Demand Controlled Ventilation

- A demand control ventilation (DCV) system is an integral part of a building’s ventilation design. It adjusts outside ventilation air based on the number of occupants and their ventilation demands / requirements.

- Heating, ventilation, and air conditioning (HVAC) is typically not considered a challenging application area when it comes to CO₂ sensors.
Demand Controlled Ventilation (DCV)

![Graph showing Demand Controlled Ventilation (DCV)]
DCV – How is Demand Realized

- People counters – Wi-Fi, motion sensors
- Light level sensors – Lights activated or daylight. Difficult to determine numbers.
- CO2 Sensors (Occupancy) – Good for small and large applications. IAQ indicator
Regulatory Considerations

- **ASHRAE 189.1 Standard for the Design of High-Performance Green Buildings**
  Places requirements on CO\(_2\) sensors in terms of accuracy and outdoor measurement.

- **ASHRAE 90.1 Energy Standard for Buildings**
  This standard provides the minimum requirements for energy-efficient design of most buildings, except low-rise residential buildings.

- **ASHRAE 62.1 Ventilation for Acceptable Indoor Air Quality**
  Provides basic guidance for CO\(_2\) sensors and their use.

- **The LEED v.4 Green Building Standard**
  Awards credits for CO\(_2\) measurement. There are also requirements relating to the accuracy, calibration interval, and maintenance of sensors.
Standards for HVAC

Indoor Air Quality
- EN 16814
- ASHRAE 62.1

Energy Performance
- EN 15251
- ASHRAE 111
- ASHRAE 90.1

Design of HVAC
- EN 13779

Performance of HVAC
ASHRAE 62.1 - CO2 Sensors for DCV

All CO2 sensors used as part of a DCV system ... shall meet the following requirements:

• Spaces with CO2 sensors ... leading to a central CO2 monitoring station shall be provided with at least one sensor for each 10,000 ft\(^2\) (1000 m\(^2\)) of floor space.
• Sensors or probes shall be installed between 3 and 6 ft (1 and 2 m) above the floor.
• CO2 sensors must be accurate to ±50 ppm at 1000 ppm.
• Outdoor air CO2 concentrations shall be determined by one of the following:
  • Outdoor air CO2 concentrations shall be dynamically measured using a CO2 sensor.
  • When documented statistical data are available on the local ambient CO2 concentrations, a fixed value typical of the location where the building is located shall be allowed in lieu of an outdoor sensor.
ASHRAE 90.1

Section 6.4.3.8 of ANSI/ASHRAE/IES Standard 90.1
Demand control ventilation (DCV) shall be provided for densely occupied spaces served by systems with one or more of the following:
   a. An air-side economizer.
   b. Automatic modulating control of the outdoor air dampers.
   c. A design outdoor airflow greater than 3000 cfm (1400 L/s).
LEED v4: Enhanced Indoor Air Quality Strategies

Carbon Dioxide Monitors

- Have in place CO2 monitors in all densely occupied spaces. Rooms smaller than 150 square feet (14 square meters) are exempt.
- CO2 monitors must be between 3 and 6 feet (900 and 1,800 millimeters) above the floor.
- Test and calibrate CO2 sensors to have an accuracy of no less than 75 parts per million or 5% of the reading, whichever is greater.
- **Sensors must be tested and calibrated at least once every five years or per the manufacturer’s recommendation, whichever is shorter.**
- Monitor CO2 sensors with a system configured to trend CO2 concentrations in intervals no greater than 30 minutes.
DCV Benefits

- Energy
- Health
- Environment
Typical Office Energy Costs

Office Equipment: 26%
Lighting: 22%
Other: 7%
Cooking: 1%
Water Heating: 1%
Refrigeration: 1%
Space Heating: 6%
Ventilation: 7%
Cooling: 29%
HVAC: 42%

Energy Savings by DCV

- DCV contributes the largest energy and cost savings
- Average 38% for all building types

Climates
- DCV more effective in cold climates
- Multi-speed fan control helping in hot climates

Savings
- Energy Star: DCV can save from $0.05-$1.00 per sqft
- Depends on climate and occupancy schedule

Sources:
- Energy Savings and Economics of Advanced Control Strategies for Packaged Air-Conditioning Units with Gas Heat (DOE, 2011)
DCV – Energy Savings

- DCV has arguably the most dramatic financial impact of any airside energy conservation measure (ECM). DCV projects have an average payback of 2.5 years with an average of 38% energy reduction in buildings. (foobot data)
Indoor Air Quality - IAQ

- WELL Building Institute - Based on the LEED and ASHRAE standards.
- Focus is shifting away from technical requirements alone, and more towards occupant wellbeing.
- 2010 the World Health Organization published an indoor air quality guide that includes guidelines for selected pollutants and discusses their potential health risks.
CO2 & Indoor Air Quality Assessment

- CO2 levels are linked to Indoor Air Quality
- High CO2 levels considered a pollutant
- Cognitive function is impaired at higher CO2 concentrations
- Chronic illness linked to CO2 exposure
- Short term and long-term studies underway
Green Building Impact Studies

 "The Impact of Green Buildings on Cognitive Function" Study

 For 6 full workdays (0900–1700 hours) in an environmentally controlled office space, participants were exposed to IEQ conditions representative of Conventional (high concentrations of VOCs) and Green (low concentrations of VOCs) office buildings in the United States. Additional conditions simulated a Green building with a high outdoor air ventilation rate (labeled Green+) and artificially elevated carbon dioxide (CO2) levels independent of ventilation.

 On average, cognitive scores were 61% higher on the Green building day and 101% higher on the two Green+ building days than on the Conventional building day (p < 0.0001).

 Cognitive function scores were significantly better under Green+ building conditions than in the Conventional building conditions for all nine functional domains.
Cognitive Scores - Conventional vs. Green Building

Source: Study by National Institute of Environmental Health Sciences
CO2 and Employee Productivity

- Information usage and strategic thinking were significantly impaired even at a concentration level of 1000 ppm.
- IAQ HVAC improvements of about $40- per person / per year can yield productivity improvements of ~8%, or $6500- per person / per year.
Employee Benefits of Better Ventilation

IAQ
- Information usage
  - Employee learning
  - Productivity
- Strategy
  - Decision-making
- Crisis response
  - Mistakes
  - Hazardous situations

- CABA: • 2-10% increase
- REHVA: • 10% increase
- USGBC: • 11% increase
- Carnegie Mellon: • 3-18% increase
Indoor Air Quality & Energy Efficiency

- Demand Controlled Ventilation can deliver both
- Combined outcomes from the same effort
- Increased Productivity and Decreased Operating Costs
Challenges for DCV
System Limitations

- Equipment Sizing
- Design OA
- Heaters and chillers
- Duct Systems
Local Climate Factors

- Heat and Humidity
- Sources of Exterior CO2
- Harmful Emissions
- Pressure Control
Covid-19 and HVAC

- Consider ventilation system upgrades or improvements and other steps to increase the delivery of clean air and dilute potential contaminants. Obtain consultation from experienced Heating, Ventilation and Air Conditioning (HVAC) professionals when considering changes to HVAC systems and equipment.
- Increase outdoor air ventilation, using caution in highly polluted areas.
- Ensure ventilation systems operate properly and provide acceptable indoor air quality for the current occupancy level for each space.
- Increase airflow to occupied spaces when possible.
- Turn off any demand controlled ventilation (DCV) controls that reduce air supply based on occupancy or temperature during occupied hours.
- Open outdoor air dampers beyond minimum settings to reduce or eliminate HVAC air recirculation.
- In non-residential settings, consider running the HVAC system at maximum outside airflow for 2 hours before and after the building is occupied.

*This is not the complete list. Visit cdc.gov for complete information*
HVAC Effect on Virus Transmission

- HVAC Systems cannot solely control infectious disease transmission
- Large droplets will not be affected by HVAC system controls
- Increasing outdoor air can serve to dilute aerosols
- Enhanced filtration can reduce the concentration of infectious aerosol particles
Sensor Technology for DCV
Sensor Integration

- Analog Signals
- Digital Serial
- Modbus
- Networked Solutions

Industry 4.0

The Five C’s of IoT
- Connectivity
- Continuity
- Compliance
- Coexistence
- Cyber Security
Sensors for DCV

Requirements

- Long term Stability – Low drift over time.
- Robust sensor – Not affected by high humidity and most contaminants
- 24/7 occupancy? (nursing homes, hospitals)
Non-Dispersive Infra-Red (NDIR) Optical CO$_2$ Measurement Technology

- Light source, filter and detector $\rightarrow$ CO$_2$ measurement
- Attenuation in intensity gives the CO$_2$ concentration (e.g. 1000 ppmCO$_2$)

- Changes in sensor structure cause drift:
  - Light source intensity change
  - Dirt in optical cuvette
  - Any mechanical changes

One IR source, one filter $\rightarrow$ CO$_2$ absorption wavelength
Infrared Absorption of the CO$_2$ Molecule

- Absorption spectrums occur when light is absorbed by the gas molecule due to vibrations and rotations of the molecule and its atoms.
- Unique fingerprint characteristics can be found for most gases.
- The strongest CO$_2$ absorption band is found at 4.26 μm (mid infrared).
- Absorption of other gases is normally negligible in the CO$_2$ absorption band.
Common NDIR Measurement Technologies

Ways to compensate for drift

- Adding components
- Using software tricks, such as so-called ABC (Automatic background calibration)
What is ABC?

- ABC = Automatic Background Calibration
- Used in low-cost NDIR CO₂ sensors
- Long-term sensor drift is minimized by an ABC algorithm:
  - During a period (several days by default) there is a constant search for the lowest CO₂ value
  - The lowest CO₂ reading is stored
  - After the period has expired, sensor rescaling is performed based on the lowest reading and expected background fresh air CO₂ concentration (400 ppm)
  - The sensor calibration is updated accordingly

- In the CARBOCAP® technology there is continuous reference measurement, and no software tricks are needed for compensation
The CARBOCAP® Sensor Technology

- Developed at Vaisala in the early 1990’s, first products in 1997
- Utilizes a Vaisala proprietary silicon based tunable infrared filter (Fabry-Perot Interferometer, FPI)
- The amount of infrared light passing through the gas is measured at two discrete wavelengths:
  - the absorption wavelength (4.26 mm), where CO₂ absorbs strongly
  - the reference wavelength (3.9 mm), where CO₂ has no absorption
- CO₂ concentration is calculated from the ratio of the two

Vaisala CARBOCAP® sensor

One IR source, One tunable filter → CO₂ and reference wavelengths = true referencing
Basic Structure of the CARBOCAP®

- Light source with reflector
- Sample cell
- FPI
- Detector
- Mirror surface
- CO₂ IR absorption
- Protective window
- IR source
- Fabry-Perot Interferometer Filter
- Detector
The 1st generation: Traditional filament lamp

- Limited lifetime
- Light power decreases over time
- High power consumption
- Needs manual assembly

The 2nd generation: New light source

- Long lifetime
- Stable light output
- Low power consumption
- Automatic assembly

Now: The Microglow
Temperature and Pressure Correction
According to Ideal Gas Law

\[ CVC = UCR \times \frac{1013 \times (t + 273)}{298 \times p} \]

CVC = corrected volume concentration (ppm or %CO₂)
UCR = uncorrected reading
p = ambient pressure (hPa)
t = ambient temperature (°C)

EXAMPLE:
– transmitter output 2000 ppm CO₂
– ambient pressure 980 hPa
– room temperature 20 °C

\[
CVC = 2000 \text{ ppm} \times \frac{1013 \times (20 + 273)}{298 \times 980} = 2033 \text{ ppm}
\]

How a reading of a 1000 ppm (at 25 °C and 1013 hPa) concentration changes with t and p according to ideal gas law

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<th>Pressure (hPa)</th>
<th>Temperature (°C)</th>
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<tr>
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<tr>
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Sensor Installation Considerations
Room Monitoring

- Representative location
- Free airflow
- No heat sources

- Restricted airflow
- In direct sunlight from window
- Close to heat sources
Some wall sensors generate a lot of heat

Mounting a temperature or humidity sensor above another wall unit is not recommended
Duct Sensors - Know How It Measures

Gas/CO₂ sensors with flow capture:

- Any leak in the sensor or mounting means you may be measuring what is outside, not inside the duct

Mitigation:

- Use sensors with measurement inside duct
- Perform thorough leak testing
Outdoor CO$_2$ Sensors

You need:
- A sensor that is designed for outdoor use
- A sensor that is fully temperature compensated over the whole outdoor temperature range
- A sensor with better accuracy and stability than your indoor sensors
Why Outdoor CO$_2$?

To get correct airflow rates

The difference between outdoor and indoor CO$_2$ concentrations is used as a proxy for occupancy measurement – how many people are in the space.
Use a Common Outdoor CO₂ Sensor

- One sensor can manage the whole building
- Limited actual measurement range
  - Small sensor drifts cause large changes in flow rates
CO$_2$: Barometric / Elevation Compensations

The barometric pressure influences the ppm calculation:

$$\text{PPM} = \frac{\text{Number of CO}_2 \text{ molecules}}{\text{Total number of molecules}} \times 10^6$$

Optical CO$_2$ instruments measure the number of CO$_2$ molecules.

Outdoor and Indoor sensors must use same pressure setting.

Active compensation is not a big advantage as long as all sensors are using the same settings/calibrations.
Error Sources: Building Exhaust Air

Indoor air gets into the outdoor sensor:
- Different temperature
- Different humidity
- Higher CO₂

Mitigation:
- Mount away from exhaust duct
- Do not mount over doors or windows that can be opened
Outdoor CO$_2$ Error Sources: Dead Spaces

Sensors mounted in areas with poor air flow and CO$_2$ from cars exhaust can build up and elevate the ambient readings.

**Mitigation:**
- Mount in open locations
- The sensor should preferably be mounted closer to the air inlet.
The Service

Maintain

Regular calibration ensures your high-precision instruments continue to provide accurate, high-quality data.
What Do I Have to Know about Calibration?

- What does my quality policy require?
  - The use and maintenance of instruments is governed by laws and regulations or the quality policy for the instrument

- How was my instrument calibrated?
  - Is the calibration traceable? Does it establish chain of traceability in my measurement?
  - What is the uncertainty of the calibration of the instrument?

- How should I calibrate?
  - Establishing calibration interval
  - Is traceable calibration needed?
Instrument Maintenance Requirements

- Calibrated in intervals before being used (following standards)
- Adjusted according to manufacturer’s instructions
- Calibrated by ISO certified providers
- Calibration and verification records kept and maintained
- Able to identify calibration status
- Protected from adjustment that could affect results of measurement
ISO 9001 Traceable Calibration

- ISO 9001, requires the organization to ensure that “…when measurement traceability is a requirement, or is considered by the organization to be an essential part of providing confidence in the validity of measurement results, measuring equipment shall be:
  - calibrated or verified…
  - identified…
  - safeguarded…”
Traceability

- Traceability is the documented chain of calibrations and references from top level of SI system to the instrument.

- If uncertainty for the measurement is not known, the traceability chain is broken.

- Without traceability to a standard, it is not a reliable or quality reference standard.

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**Diagram:**

- **SI**
- **Primary reference**
- **Secondary reference**
- **Reference standards**
- **Working standards**
- **Measurement equipment**

**Labels:**

- BIPM / IBWM
- National laboratories
- Accredited laboratories
- End users

**Degree of uncertainty in the measurement**
Methods of Calibration

**Calibration**
- Comparison with calibrated reference
  - Portable or duplicate
- Calibrator Kit
- Analog Calibration

**Adjustment**
- Laboratory Service
- Calibration Kit – Multi-Point
- One Point Adjust with Portable
Exchange of Measurement Modules

Replacement Sensor Modules

- Instrument remains in service
- Calibration certificate included
- Low maintenance effort and cost
Spot check with a portable meter

Methods for a portable meter:

1. Use portable meter as calibration reference for permanently installed meter
2. Spot check periodically instead of removing the permanently installed meter

How to incorporate portable meter into your system:

- When using as a reference for permanently installed meter, be sure the probe is very close to installed meter to ensure best results
  - Connect portable meter to installed unit via a cable. Both values are visible on portable meter (if using Vaisala HM70 or GM70 meter)
Calibration of Reference Instruments

Monitoring and Measuring Resources Process:

- Determine resources needed for accurate results
- Provide resources
- Measure to verify products/services against requirements
- Document results for monitoring
- Traceable calibrations
Conclusion

Accurate HVAC Measurement

Energy Consumption

Certificate Acquisition

Employee Productivity
...it’s more important than ever to base decisions on accurate and reliable data.
Thank You