Preliminary Evaluation of Commercial Indoor Air Quality Sensors for Application to Aircraft Cabin Air Measurements

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• Introduce the overall program objectives
• Highlight relevant aircraft system information
• Provide brief overview of experimental setup
• Discuss Fourier Transform Infrared Spectroscopy (FTIR)
• Report initial commercial CO$_2$ sensor data
• Conclude with recommendations & proposed future work
Identify commercial sensors that have potential for aircraft cabin air quality sensing for multiple gases

Determine reliability and operation characteristics of commercial sensors in different pressure and background gas operating environments

Investigate current sensor technologies to determine areas where improvements can be made
Aircraft System Overview

- Cabin pressure control valve
- Ozone catalytic converter (2 locations)
- Air-conditioning packs (2 locations)
- Recirculation system (2 locations)
- Engine (2 locations)
- Passenger compartment air distribution
- Mix manifold
Environmental Control Systems

- Bleed Air System
- Mix Manifold System
- Recirculation System
- Cabin Ventilation System
Bleed Air System

• Totally automatic system, except for an emergency shutoff available to pilots

• Outside air entering the airplane is compressed to 220 kPa (2.2 atm) and rises to a temperature near 160 °C (320 °F)

• Number of valves and heat exchanger provides air at proper temperature and pressure to numerous flight system
  • Air conditioning packs
  • Cabin ventilation and pressure system
  • Potable water pressurization
  • Wing and engine anti-ice protection
Mix Manifold System

- Air entering cooled by air conditioning system and decompressed
  - Temperature = 15 °C (59 °F)
  - Relative Humidity = 5%
  - Pressure = 82 - 78 kPa (6,000-7,000 ft altitude) (0.81-0.77 atm)

- $\text{CO}_2 / \text{CO}$ unchanged from outside

Ref. 1
Recirculation System

- Re-circulated air is essentially sterile

- HEPA filters remove 99.9+% of bacteria and viruses produced by passengers
  - Filters similar to those used in critical wards of hospitals
  - Harmful gases are NOT removed by filters

- Attempted control of gases to low levels in the cabin through dilution with high quantities of outside air

Ref. 1,3,6

![Outside air changes per hour chart]

- Airplane: 10-15
- Hospital delivery and operating rooms: 5
- Typical building: 1-2.5
Cabin Ventilation System

- Air flow is directed from below floor to overhead cabin
  - Temperature = 18-30 °C (64-86 °F)
  - Relative Humidity = 10-20%

- Provides approximately 1.9 L/s of oxygen
  - Human at rest consumes 0.007 L/s

- No sensors or monitoring of potentially harmful gases
  - Assumed below harmful levels through dilution

Ref. 1,7
Experimental Setup
Experimental Setup – Control Module

Controls system settings for pressure and gas environment

Gas lines rated for pressures up to 12,000 feet (50.5 kPa, 0.5 atm)

Test & Inert Gas Flow Meters

Altitude Readouts

inHg Vac & ft above sea level
Experimental Setup – Commercial Sensor Module

- 7 CO₂ Sensors
- 4 Temperature Sensors
- 2 Relative Humidity Sensors

ACER
Airliner Cabin Environment Research
www.acer-coe.org
Experimental Setup – FTIR Module

- Variable path length gas chamber cell
  - Model M-5-22-V
- Optical path folded in a volume of 8.5 L
- Cell path length = # of passes * length of base path
  - Length of base path = 56 cm
  - Min # of passes = 4
  - Min cell path length = 2.24 m

Perkin Elmer FTIR System: Spectrum GX
FTIR Analysis
FTIR – Pressure Effects

- Airplane cabin pressure is approximately that of air pressure at 6,000 to 8,000 feet above sea level
  - \( \sim 81\text{-}75\% \) of sea level pressure

Pressure \( [\text{kPa}] = 101.325 \times (1 - 2.25577 \times 10^{-5} \times \text{altitude in meters})^{5.2558} \)

http://www.engineeringtoolbox.com/air-altitude-pressure-d_462.html
FTIR – Pressure Effect cont.

Temperature range of 20 °C
Ideal partial pressure sensor at 7,000 ft would read 2977 [ppm] for 5000 [ppm] STP

\[ n = P \frac{V}{RT} \]
FTIR Analysis

CO2 Partial Pressure vs. Total Pressure

- Ideal CO2 Partial Pressure at Altitude
- FTIR CO2 Partial Pressure
- CO2 Partial Pressure at Sea Level

Graph showing the relationship between CO2 partial pressure and total pressure across various altitudes. The graph includes linear equations and their R² values:

- \( y = 0.0007x - 0.0278 \) (for Ideal CO2 Partial Pressure at Altitude)
- \( y = 0.0007x - 0.0284 \) (for FTIR CO2 Partial Pressure)
- \( R^2 = 0.9901 \) (for CO2 Partial Pressure at Sea Level)

Number of Scans = 1
Range = 4000 – 600 cm\(^{-1}\)
Resolution = 0.5 cm\(^{-1}\)
Interval = 0.1 cm\(^{-1}\)
FTIR Analysis

Number of Scans = 1
Range = 4000 – 600 cm\(^{-1}\)
Resolution = 0.5 cm\(^{-1}\)
Interval = 0.1 cm\(^{-1}\)

\[
y = 4.06x - 14.36 \\
R^2 = 0.98
\]

(0.67 atm)
CO₂ Commercial Sensor Initial Testing Results

• K-22 LO Sensor
• Siemens QPA2000
• Airstest EE80
• Airstest TR9294
• Johnson Controls CD-WAO
• SenseAir aSense mIII
• CO₂ has several absorption bands with the 4.26 μm (2349 cm⁻¹) band being the most widely used
  • Wavelength provides the least interference by other common components in air

• Typical systems utilize 2-step drying system to remove water vapor in sample air

• Degradation of IR light source over time
(A1,A2) K-22 LO Sensor

- NDIR CO2 Sensor
  - Automatic Baseline Correction (ABC) of ~400 ppm as set point
  - Range: 0 – 2,000 ppm
  - Accuracy: ± 75 ppm ± 5% of measured value

- Single IR lamp source with monitoring of a single wavelength
(A3) Siemens QPA2000

- NDIR CO2 Sensor
  - Range: 0 – 2,000 ppm
  - Accuracy: ± 50 ppm ± 2% of measured value
  - Temp Dependence: 2 ppm/°C

- Dual IR lamp source with monitoring of a single wavelength
(A4) AirTest EE80

- NDIR CO2 Sensor
  - Range: 0 – 2,000 ppm
  - Accuracy: ± 50 ppm ± 2% of measured value
  - Temp Dependence: 5 ppm/°C

- Dual IR lamp source with monitoring of a single wavelength

- Auto-calibration procedure compensates for aging of the IR source
• NDIR CO2 Sensor
  • Automatic Baseline Correction (ABC)
  • Range: 0 – 2,000 ppm
  • Accuracy: ± 20 ppm ± 3% of measured value

• Single IR lamp source with monitoring of a single wavelength

• Use of “oval sensor element” to create longer path-length to measure CO2
  • Increased IR path-length allows higher signal-to-noise ratio
(A6) Johnson Controls CD-WAO

- **NDIR CO2 Sensor**
  - Range: 0 – 2,000 ppm
  - Accuracy: ± 30 ppm ± 2% of measured value

- **IR lamp source with monitoring of a dual wavelengths**
  - Tunable filter allows for measurement at two wavelengths

- **Auto-calibration procedure compensates for aging of the IR source**
(A7) SenseAir aSense mIII

- NDIR CO2 Sensor
  - Automatic Baseline Correction (ABC)
  - Range: 0 – 2,000 ppm
  - Accuracy: ± 20 ppm ± 5% of measured value

- Single IR lamp source with monitoring of a single wavelength
Test Date: 8-23-2010
Start Time: 11:15 AM
End Time: 3:05 PM
Flow Rates: 1.0 sccm CO₂; 499.0 sccm N₂
Altitude (Pressure): 10,780 ft (67.5 kPa, 0.67 atm)
Expected Final CO₂ Concentration: 1332 [ppm]

Commercial CO₂ Performance

CO₂ Sensor Performance Compared to FTIR

Time is from introduction of CO₂ gas
Commercial CO$_2$ Performance

Test Date: 8-27-2010
Start Time: 8:35 AM
End Time: 12:30 PM
Flow Rates: 1.5 sccm CO$_2$; 498.5 sccm N$_2$
Altitude (Pressure): 10,780 ft (67.5 kPa, 0.67 atm)
Expected Final CO$_2$ Concentration: 1997 [ppm]
• Sensor drift due to automatic baseline correction (ABC) algorithms
  • Algorithms typically use a set time period to calculate the baseline reference value

• ABC algorithms used to compensate for difficult to decouple effects of IR sensing technology
  • Long-term degradation in IR lamp source(s)
  • Collection of dust & water vapor condensation on IR beam window
Recommendations

• As-is commercial CO$_2$ sensors may need to be modified to overcome the issues associated with the automatic baseline correction algorithms

• Long-term ABC algorithms may not be appropriate for sensor operation in an aircraft cabin environment
  • Sensors that monitor a known reference sample and quickly reset their baseline value may be more applicable

• Sensors without baseline correction that are replaced at regular intervals to reduce the effects of IR source aging may be an alternative
Future Work

- Additional testing with CO₂ sensors to determine exact effects of automatic baseline correction (ABC)

- Attempt to bypass ABC within commercial sensors to directly test the IR sensor performance

- Explore other CO₂ sensing technologies as potential replacement for IR based devices

- Perform similar testing on commercial CO and O₃ sensors
Conclusions

- Experimental setup allows for accurate reproduction of aircraft cabin pressure environment to study commercial sensors.

- FTIR module allows for accurate determination of gas concentration for use as standard comparison for all commercial sensors.

- Commercial CO\textsubscript{2} sensors produced for building environments may need modifications to accurately work in an aircraft cabin.

- Multiple approaches within CO\textsubscript{2} IR sensor technology experience similar operational issues when studied in an aircraft cabin environment.
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  • L. C. Mathison
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Additional Information
FTIR Analysis Background
• Energy of molecule comprised of three additive components
  • Rotation of molecule as whole (1 cm⁻¹ to 10² cm⁻¹)
  • Vibration of constituent atoms (10² cm⁻¹ to 10⁴ cm⁻¹)
  • Motion of electrons (10⁴ cm⁻¹ to 10⁵ cm⁻¹)

• IR absorption originates in photons that are absorbed by transitions between two vibrational levels
FTIR – Principles of Operation cont.

• All polyatomic molecules and hetero-nuclear diatomic molecules absorb IR radiation

• Pattern of absorption determined by physical properties of molecule
  • Number of atoms, bond angles, bond strengths

• Interpretation of spectra involves correlation of absorption bands of an unknown gas with known absorption frequencies for bond types

• Each spectrum differs from all others and is considered a molecular signature
Experimental Setup – FTIR Module
• Current QASoft database covers 386 gases
  • Compounds that have a vapor pressure 1 atm at room temperature (standard conditions)

• IR spectra of database covers 3700 cm\(^{-1}\) to 500 cm\(^{-1}\)
  • Fundamental IR region where rotation and vibrations of molecules give rise to IR absorption

• Strongest spectral features most often used in measurements
  • Regions where absorbance is proportional to concentration-path length product

• Intensity of absorption depends on total number of molecules present in path of radiation
IR Spectrum of CO₂

- 3 distinct modes of vibration

- Symmetrical motion of O atoms, C atom fixed
  - $\omega_1 = 7.5 \mu$ ($k_1 = 1337$ cm$^{-1}$)
  - Inactive in IR (lack of dipole moment)

- C oscillates perpendicular to O atoms, $\beta$(OCO)
  - $\omega_2 = 15 \mu$ ($k_2 = 667$ cm$^{-1}$)

- Asymmetrical vibration, C moves relative to center of mass of O atoms
  - $\omega_3 = 4.3 \mu$ ($k_3 = 2349$ cm$^{-1}$)

Ref. 8
• Theoretical: $k_2 = 667 \text{ cm}^{-1}$
  • Database: $k_2 = 667.2 \text{ cm}^{-1}$
  • Absorbance = 0.63

• Theoretical: $k_3 = 2349 \text{ cm}^{-1}$
  • Database: $k_3 = 2339.9 \text{ cm}^{-1}$
  • Absorbance = 0.31
  • Database: $k_3 = 2364.3 \text{ cm}^{-1}$
  • Absorbance = 0.37

• Absorbance scale adjusted to 100 ppm-meters

From QASoft Database
Vacuum Chamber
Temperature Monitoring
During Sensor Testing
Temperature Monitoring

Test Date: 8-23-2010
Start Time: 11:15 AM
End Time: 3:05 PM

Increase of ~2.5°C corresponds to max of 12.5 [ppm] CO₂ drift due to temp
Temperature Monitoring

Test Date: 8-27-2010
Start Time: 8:35 AM
End Time: 12:30 PM

Vacuum Chamber Temperature

A4 - Temp
A6 - Temp
Vacuum Chamber
Relative Humidity Monitoring During Sensor Testing
Relative Humidity Monitoring

Test Date: 8-23-2010
Start Time: 11:15 AM
End Time: 3:05 PM

Vacuum Chamber Relative Humidity

- A11 - Humidity
- A12 - Humidity
Relative Humidity Monitoring

Test Date: 8-27-2010
Start Time: 8:35 AM
End Time: 12:30 PM

Vacuum Chamber Relative Humidity

- A11 - Humidity
- A12 - Humidity

Time [min]
CO$_2$ Commercial Sensor Previous Results

- SenseLife CAM CO$_2$ Meter
- Gray Wolf Multi-gas Sensor IQ-604
- NDIR CO$_2$ Sensor
  - Automatic background calibration
  - Range: 0 – 9,999 ppm
  - Accuracy: ± 75 ppm + 5% of measured value

- Sensor automatically resets baseline value according to minimum CO$_2$ concentration observed over a given time period
• **NDIR CO$_2$ Sensor**
  • Range: 0 – 10,000 ppm
  • Accuracy: ± 50 ppm + 3% measured value

• **Electrochemical CO Sensor**
  • Range: 0 – 500 ppm
  • Accuracy: ± 2 ppm < 50 ppm
    ± 3% measured value > 50 ppm

• **PID O$_3$ Sensor**
  • Range: 5 – 20,000 ppb
  • Accuracy: Not provided
Sensor Comparison
Pre-mixed CO$_2$/N$_2$ Gas
References
References


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