Sensing Technology for measuring Particle Number & Mass in Indoor Environments

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Cambridge Particle Meeting – June 28th 2019
Overview

• Who We Are & What We Do
• Why care about indoor air quality?
• Sensing technology for indoor air quality
• NAQTS V2000
  • Particle Number - CPC
  • Particle Mass – Laser light scattering
• Applications
  • Indoor Air Quality (IAQ) - Homes & Schools
  • Vehicle Interior Air Quality (VIAQ)
• Conclusions
Who We Are and What We Do

National Air Quality Testing Services (NAQTS) is a social business that is passionate about improving the quality of life.

We seek to **improve awareness of indoor air quality** through widespread public and commercial monitoring using our holistic, high-quality, air pollution monitoring technology.

Based in UK (Lancaster University Environment Centre and Cardiff), Ann Arbor, Michigan, USA, and Guangzhou, China.

**INDOOR AIR QUALITY & ENERGY EFFICIENCY**
Developing models for assisting building design and modification whilst ensuring energy efficiency and good indoor air quality.

**CITIZEN SCIENCE - INDOOR:OUTDOOR AIR QUALITY**
Air quality toolkits for citizen science measurements. Capturing real-time pollution levels during school drop off/pick up times, as well as levels of student exposure in the classroom.

**OCCUPATIONAL HEALTH AND SAFETY**
Evaluation of exposure to nanomaterials

**AIR QUALITY MAPPING**
Routine mobile monitoring for measuring time-integrated concentrations at high spatial resolution

**BENCHMARKING VEHICLES “COMFORT”**
Air Quality, Noise, and Vibration
Data on in-cabin comfort from 100s of vehicles per year
Why care about indoor air quality?

• ~87% of our time indoors
  • In a vehicle (5.5%)
  • In a residence (68.7%)
  • Office/factory (5.4%)

• Significant indoor sources from everyday activities

• Potential for indoor air pollution to get “trapped”

• Lack of public & political awareness
NAQTS V2000

- **PN** - CPC with 20:1 pre-dilution (IPA, \(d_{50}\) 15nm)
- **PM** – Laser light scattering
- **CO, NO\(_2\), NO** – Electrochemical
- **CO, NO\(_2\), VOCs** – Metal Oxide
- **VOCs** – Real-time and thermal desorption tubes for GC-MS Analysis
- **CO\(_2\)** – NDIR
- **T, P, RH** – BME280
- **Vibration** – 3D accelerometer and 3D Gyro
- **Noise** – dBA
- **Vibration** – 3D accelerometer and 3D Gyro
- **Web GUI** with SQL Database
- **GSM**

Integrated measurement device for a “holistic” understanding of air quality
Our CPC Technology

- Regulatory grade PN: ISO 27891
- Full mixing “fast” CPC
- 20:1 pre-dilution (IPA, $d_{50}$ 15nm)
Low Cost PM Technology

- Low-cost sensors can help us identify pollution sources, better understand personal exposure, and complement existing networks to increase the spatial resolution of measurements.
- **BUT low cost sensors ≠ low cost air quality monitor!**
- What is “good enough” data?

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### IoT deployment for city scale air quality monitoring with Low-Power Wide Area Networks

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Particulate matter sensors Alphasense OPC-N2, Plantower PMS5003,  
Plantower PMS7003, Honeywell HPMA115S0

<table>
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<tr>
<th>Sensor</th>
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<td></td>
<td>RMSE</td>
<td>$R^2$</td>
<td>RMSE</td>
<td>$R^2$</td>
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<td>Alphasense OPC-N2</td>
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<td>0.038</td>
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Low Cost PM Technology

- By measuring both ultrafine, fine, and coarse particles, we can get a better understanding of indoor aerosol characteristics and source apportionment.
- Combustion particulates dominated by UFP.
- Re-entrained particles dominated by coarse mode.

**Table:**

<table>
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<tr>
<th>Parameter</th>
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<th>Typ.</th>
<th>Max.</th>
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<td>+/-10</td>
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<td>Warm-Up Time</td>
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<tr>
<td>Response Time</td>
<td>(t_{\text{resp}})</td>
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<td>—</td>
<td>s</td>
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</table>

**Figure 1: Detection Principle**
Low Cost PM Technology - Colocation

• Extensive colocation activities at Guangzhou Institute of Geochemistry, Chinese Academy of Sciences Supersite to quantify, and improve low-cost sensor accuracy

• We are doing our due diligence on low-cost PM sensors currently
Indoor Air Quality - Homes

- 68.7% of our time in a residence
- Significant indoor sources from everyday activities
- More time spent here by vulnerable populations

Summary of PNC from various activity influenced periods (Isaxon et al., 2015)
Indoor Air Quality - Homes

- Measurements in four homes across the UK for Clean Air Day 2019, using the V2000
- Investigating role of location and activity on indoor PN concentrations
- 10 min rolling averages (1s data)

- Indoor 7x more polluted than outdoors
- Largest PNC from toast, gas stove, and wood burner
- Penetration of outdoor particles correlate with train timetable
- Long decay rates

- Indoor 60% more polluted than outdoors
- Largest PNC related to cooking activities
- Long decay rates
Indoor Air Quality - Homes

- Location less important in determining indoor concentrations, however, evidence of ingress
- Role of individual activities important
- Simple actions can be taken to minimise exposure
- Illegal concentrations outside, legal concentrations inside
- We need more measurements in homes to better understand the problem
- What about energy efficiency?

- Indoor 47% more polluted than outdoors
- Largest PNC concentrations from toast and frying steak
- High outdoor background concentrations

- Indoor 3x more polluted than outdoors
- Largest PNC related to cooking activities
- Some correlation between outdoor and indoor peaks suggesting PN infiltration
Indoor Air Quality - Schools

- Children are especially susceptible to air pollution (Pope & Dockery, 2006)
- Poor IAQ associated with poor academic performance (Mohai et al., 2011).
- Children spend a significant amount of time at school: ~190 days per year, and ~30 hours per week.
Vehicle Interior Air Quality (VIAQ)

- 5.5% of our time in a vehicle
- Immediate proximity to significant pollutant sources (other vehicles), plus in urban areas, high outdoor concentrations

NHAPS - Nation, Percentage Time Spent
Total n = 9,196

- IN A RESIDENCE (68.7%)
- IN A VEHICLE (5.5%)
- OFFICE-FACTORY (5.4%)
- OTHER INDOOR LOCATION (11%)
- BAR-RESTAURANT (1.4%)

- TOTAL TIME SPENT INDOORS (86.9%)
- OUTDOORS (7.6%)
Effect of Occupant Behaviour

- **Ingress Ratio** – How much outside air pollution is getting into the cabin?

- **Stuffiness Factor** – How well is the vehicle ventilating CO₂?

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<th>INGRESS RATIO</th>
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<td>Recirculation On</td>
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<td>Recirculation Off</td>
<td>60%</td>
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<tr>
<td>Recirculation On</td>
<td>13%</td>
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Effect of Occupant Behaviour

- **Ingress Ratio** – How much outside air pollution is getting into the cabin?

- **Stuffiness Factor** – How well is the vehicle ventilating CO₂?

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<td>Recirculation On</td>
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<tr>
<td>Recirculation Off</td>
<td>41%</td>
<td>1.4</td>
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<tr>
<td>Recirculation On</td>
<td>17%</td>
<td>4.97</td>
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Effect of Occupant Behaviour - Summary

- These data show the heterogeneity of Ingress Ratios
- 24-99% with recirculation mode off, 5-17% with recirculation mode on
- An inherent tradeoff between protecting passengers from ambient ingress, and adequate ventilation
- Huge influence of passenger habit on dose. By driver education, and automation of HVAC controls, exposure can be reduced significantly
Effect of Occupant Behaviour

- Drive from Long Beach to Downtown LA
- ~ 2 hours in length
- A variety of HVAC settings
  - “Fresh Air” mode
  - Recirculation mode
- A variety of speeds
  - High
  - Low
  - Stop/start
- A variety of locations
  - Urban
  - Highway
Effect of Occupant Behaviour – ”Fresh Air” Mode

- PN peaks at 100,900 #/cm³
- Vehicle is well ventilated, with CO₂ concentrations <1000ppm
- VIAQ is susceptible to extremely localized air quality: dirty diesels!
Effect of Occupant Behaviour – Recirculation Mode

- PN exponential decay to low concentrations
- CO₂ peaks at >3500ppm
- Increased leakage of HVAC associated with higher speeds, results in some CO₂ ventilation, and some PN infiltration
- Obvious dichotomy between PN & CO₂
Effect of Occupant Behaviour – Recirculation Mode

- Independent ratings to quantify and compare to empower consumers
- Driver choice between PN from fresh air mode and CO₂ build-up from recirculation mode
- No correlation suggests no trade-off – independent design decisions
- Trade-off is more likely on design cost
Conclusions

- Increasing importance of measuring indoors
- Measurements must be holistic and include UFP and larger size fractions
- Role of individual action in the indoor environment important
- More measurements needed to quantify the problem
- Need to be clear in defining what data is "good enough?"