Indoor Aerosol Dynamics in Residential Buildings

Brandon Boor, Ph.D., Assistant Professor of Civil Engineering, Purdue University
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Brandon E. Boor, Ph.D., Assistant Professor, Lyles School of Civil Engineering
Herrick Laboratories & Center for High Performance Buildings, Purdue University
Indoor particulate(s) matter!

we spend 90% of our time indoors

Americans live to 79 y (on avg.)
spend 70 y inside buildings
50 y inside home
26 y asleep
5 y outdoors
4 y in transport

(ref: Prof. Richard Corsi)

we are surrounded by a fascinating mixture of liquid & solid particles from few nm to tens of μm

# concentrations: 1,000 to > 1,000,000 particles per cm³

with each breath, we inhale several million aerosols, most are < 100 nm

focus of seminar on nano-sized & biological particles

exposure associated w/ adverse health outcomes

nano-sized particles penetrate deep into our lungs, causing oxidative stress & chronic inflammation

bioaerosols (bacteria, fungi, allergens) can both cause, and protect against, asthma & allergies

we need to develop a deeper understanding of the fundamental processes that control the generation & removal (e.g. filtration) of indoor aerosols

such research will help us works towards buildings that promote human health & well-being
Indoor aerosol research group at Purdue

Research objective: to explore how people and building systems shape indoor air quality.

Ongoing research projects:
1. investigating the formation of indoor nanoaerosols down to one nanometer due to VOC reactions w/ ozone & radicals.
2. characterizing how infants & adults resuspend bioaerosols (bacteria, fungi) from flooring.
3. developing a test methodology to load HVAC filters.
4. evaluating nanoaerosol dynamics in a net-zero energy residence and biomass-burning Kenyan kitchens.
5. measuring VOC emissions from people in real-time using proton transfer reaction time-of-flight mass spectrometry.

Ph.D. students: Tianren Wu, Danielle Wagner, Jinglin Jiang

Funding:
Presentation overview

1. Background on indoor aerosol dynamics and size distributions
3. Study 2: human-driven resuspension of biological particulate matter (bioPM) from carpets
Indoor aerosol dynamics in residential buildings: source and loss processes

+ source processes: $S_{D_p}$ (#/h)

1. outdoor aerosols delivered indoors via mechanical & natural ventilation + infiltration

2. direct indoor emissions: e.g. cooking, indoor combustion, resuspension

3. nucleation of gas-phase precursors: e.g. $O_3 +$ VOCs to form secondary organic aerosol

need to measure

\[
\frac{dC_{iD_p}(t)}{dt} = \frac{S_{D_p}(t)}{V} - \frac{L_{D_p}(t)}{V}C_{iD_p}(t)
\]

need to measure

- loss processes: $L_{D_p}$ (1/h)

1. indoors aerosols delivered outdoors via mechanical & natural ventilation + exfiltration + localized exhaust

2. deposition to indoor surfaces due to gravitational settling, Brownian motion, turbulent diffusion

3. in-duct HVAC filtration

4. portable air purification

5. particle growth via coagulation

mathematical framework: aerosol physics-based material balance models

many source & loss processes are a strong function of particle size ($D_p$) and change over time.
Indoor aerosol size classifications and distributions

- **Fine aerosol:** \( \leq 1,000 \text{ nm} \)
- **Nanoaerosol (UFPs):** \( \leq 100 \text{ nm} \)
- **Coarse aerosol:** \( > 1,000 \text{ nm} \)

- **Nanocluster mode:** 1-3 nm
- **Nucleation mode:** 3-10 nm
- **Aitken mode:** 10-100 nm
- **Accretion mode:** 100-1,000 nm
- **Coarse mode:** 1-100 µm

**Number concentration, \( N (\text{cm}^{-3}) \)**

**Gas-to-particle conversion**

**Organic aerosol, sulfates, nitrates, ammonium, black carbon, sea salt, engineered nanomaterials**

**Bacterial cells & fungal spores**

**Mineral dust, road dust, ash, pollen**

**Human hair**
Number → surface area → volume → mass: different size particles matter for each distribution

**Number Distribution**
- dominated by nanoaerosol (1 to ~200 nm)
- nanoaerosol UFP

**Surface Area Distribution**
- dominated by accumulation mode (100 to 1,000 nm)
- LDSA

**Volume Distribution**
- dominated by accumulation & coarse modes (100 to 10,000 nm)
- $D_p^3$

**Mass Distribution**
- dominated by accumulation & coarse modes (100 to 10,000 nm)
- $D_p^3 \times \text{density}$

**Particulate Matter**
- PM$_{10}$
- PM$_{2.5}$
- PM$_1$
Two studies on indoor aerosol dynamics in residential buildings

structure of both studies: integrate real-time aerosol size distribution measurements with a material balance model to determine source and loss rates

ReNEWW House: nano

+ source processes
  cooking w/ electrical kitchen appliances, outdoor aerosols

- loss processes
  ventilation (AHU+ERV), filtration, exfiltration, deposition, inter-zonal airflow

resuspension: bio

chamber

+ source processes
  resuspension of settled dust, mostly > 1 μm

- loss processes
  deposition (gravitational settling), ventilation
Study 1: nanoaerosol dynamics in the Purdue Retrofit Net-zero: Energy, Water, and Waste (ReNEWW) House
Lead Ph.D. student: Jinglin Jiang
Purdue ReNEWWW House: site overview

- originally built in 1928
- renovations: 2013-2015
- solar PVT system & GSHP
- occupied by 3 graduate students (Whirlpool)
- focus on kitchen area: oven, cooktop, toaster, microwave oven, kitchen hood

HVAC system: AHU + ERV, MERV 11 filter

Purdue Biowall in living area: VOC removal
Field measurements: aerosols, energy-use profiles, smart thermostats

scanning mobility particle sizer (10-300 nm), optical particle sizer (300-10,000 nm)

outdoor sampling

kitchen hood efficiency

AC current transducer

electrical energy monitoring system w/ online platform

Ecobee3 lite
Material balance model for ReNEWW House

\[
\frac{dC_i}{dt} = \frac{S}{V} - LC_i
\]

\[
V \frac{dC_i}{dt} = E + (1 - \eta)(C_o Q_{OA}) F + C_{BM} Q_{iz} + pC_o Q_I
\]

\[-C_i \{\beta V + Q_{OA} + Q_R[1 - (1 - \eta)F] + Q_I + Q_{iz} + \eta_{hood} Q_{hood}\}\]

four HVAC operational modes

1. AHU off, ERV off
   
   \[S_1 = E + C_{BM} Q_{iz} + pC_o Q_I\]
   \[L_1 = \beta + \frac{Q_I}{V} + \frac{Q_{iz}}{V}\]

2. AHU on, ERV off
   
   \[S_2 = E + C_{BM} Q_{iz} + pC_o Q_I\]
   \[L_2 = \beta + \frac{Q_I}{V} + \frac{Q_{iz}}{V} + Q_{R,2}[1 - (1 - \eta)F_2]\]

3. AHU on, ERV on, main floor heating off
   
   \[S_3 = E + (1 - \eta)(C_o Q_{OA,3}) F_3 + C_{BM} Q_{iz} + pC_o Q_I\]
   \[L_3 = \beta + \frac{Q_{OA,3}}{V} + \frac{Q_I}{V} + \frac{Q_{iz}}{V} + Q_{R,3}[1 - (1 - \eta)F_3]\]

4. AHU on, ERV on, main floor heating on
   
   \[S_4 = E + (1 - \eta)(C_o Q_{OA,4}) F_4 + C_{BM} Q_{iz} + pC_o Q_I\]
   \[L_4 = \beta + \frac{Q_{OA,4}}{V} + \frac{Q_I}{V} + \frac{Q_{iz}}{V} + Q_{R,4}[1 - (1 - \eta)F_4]\]
Linking energy-use profiles to nanoaerosol concentrations

- **Energy monitoring system**
- **Smart thermostat**
- **Electrical kitchen appliance usage**
  - *Combustion sources seldom used*
- **HVAC operational mode**
- **Emission rate for cooking**
- **Total source rate**
- **Source rate of HVAC system**
- **Loss rate**
- **Building characteristics**
- **Indoor nanoaerosol concentration**
Electrical kitchen appliance energy use-profiles by hour and week

Real-time energy use-profiles tell us exactly when source is active and for how long: essential in characterizing transient aerosol sources in homes.

Less uncertainty than activity logs.
AHU & ERV runtimes inform aerosol source & loss processes in residential HVAC systems on a time-resolved basis

AHU (w/ ERV off): recirculation w/ filtration (MERV 11)

real-time energy-use monitoring informs HVAC operational mode & period

AHU runtime varies hour-by-hour and week-by-week

nanoaerosol loss rate is strongly linked to AHU runtime, e.g. off: no HVAC filtration!

peak in morning
AHU & ERV runtimes inform aerosol source & loss processes in residential HVAC systems on a time-resolved basis.

AHU w/ ERV on:
outdoor air, recirculation w/ filtration (MERV 11)

ERV on nearly a fixed hourly schedule: ~36%

ERV energy-use data tells us exactly when outdoor air entering/leaving house

ERV outdoor airflow rate: 60-80 cfm
Diurnal trend in AHU & ERV runtimes

AHU supply airflow rate to main floor: 450-700 cfm

runtime ~35% during sleep periods: HVAC loss rates at a minimum

peak in AHU run-time from 7 to 11 AM when occupants wake-up

ERV on nearly a fixed hourly schedule: ~36%. Thus, only 1/3rd of the time outdoor air is deliberately delivered to house via ERV.

runtime independent of active indoor aerosol sources – potential for IAQ-based HVAC control
Linking energy-use profiles to nanoaerosol concentrations: cooktop emissions
Linking energy-use profiles to nanoaerosol concentrations: toaster emissions
Impact of electrical cooking appliance type on nanoaerosol concentrations

total nanoaerosol # concentrations: 1,000 to 15,000 cm$^{-3}$

- oven: strongest emitter
- electrical kitchen appliance use-profiles automatically detect emission source
- cooktop and toaster comparable
- low emissions from microwave

N$_{10-100}$ [cm$^{-3}$]
Impact of electrical cooking appliance type on aerosol size distributions

- Most numerous particles emitted during cooking are < 100 nm.
- Mass dominated by coarse-mode > 1 μm.
- Mode for number distributions: 30-50 nm, generally unimodal.
- Aerosol source: Indoor emissions vary with size, particles from < 10 nm to 10 μm are emitted during cooking.

Assumed spherical particles of unit density.
Impact of time of day on aerosol size distributions

- **Most numerous particles throughout the day** are < 100 nm.
- **Elevation in coarse-mode aerosol** during awake/active periods: 12PM to 12AM.
- **Number concentrations greatest** btw. 20-50 nm during lunch & dinner when sources are active.
- **Number concentration mode** shifts to larger particles during middle of the night.

Assumed spherical particles of unit density.
Diurnal trend in nanoaerosol to total aerosol concentration ratio

particles < 100 nm contribute ~60-95% of the total aerosol population on a number-basis

nanoaerosol ratio peaks during lunch and dinner periods when indoor emissions are active
Diurnal trend in indoor/outdoor (I/O) nanoaerosol concentration ratio

- Surprisingly, outdoor nanoaerosol levels > indoor levels
- Wide diurnal variation in I/O ratio: 20 to 100%
- I/O ratio at a minimum between 9 and 11 AM due to morning traffic around Purdue campus – outdoor source stronger than indoor
- I/O ratio peaks in evening due to dinner: more frequent activation of indoor emission sources & reduced traffic
Energy-use patterns inform probability density functions of nanoaerosol source rates by electrical cooking appliance type

cooking emits billions of particles/minute! Emission (source) rates for different cooking appliances varied from 10 billion to 100 trillion #/h

ERV off source likely infiltration

ERV on source rates suggest importance of ERV in delivering outdoor aerosols indoors: ERV on > ERV off

toaster and oven source rate distributions are similar, cooktop is greatest

variations in source rates for each appliance suggest variable emissions due to food being cooked and how
Energy-use patterns inform probability density functions of nanoaerosol loss rates by HVAC system operational mode

**median loss rates:**

- AHU OFF, ERV OFF: 1.43 h\(^{-1}\) (narrow)
- AHU ON, ERV OFF: 3.54 h\(^{-1}\) (wide, long tail, peak \(\sim\) 2 h\(^{-1}\))
- AHU ON, ERV ON: 3.7 h\(^{-1}\) (wide, peak \(\sim\) 3.5 h\(^{-1}\))

Nanoaerosol loss rates strongly linked to AHU/ERV runtime, e.g. off: no HVAC filtration!

Variations due to size distributions, internal airflow and mixing conditions, exfiltration.

Total loss rates: sum of HVAC loss processes: filtration, duct deposition, ventilation via ERV, along with: deposition, exfiltration, inter-zonal airflow.
ReNEWW House conclusions

• Electrical energy monitoring system can be used to identify, in real-time, aerosol source and loss processes

• AHU/ERV runtimes are variable – strongly linked to time-dependent changes in HVAC source/loss processes

• Cooking activities were found to dominate the emissions of indoor nanoaerosols, often elevating indoor nanoaerosol concentrations beyond $10^4$ #/cm$^3$

• Loss rates were found to be significantly different between AHU/ERV off and on conditions, with median loss rates of 1.43 h$^{-1}$ to 3.7 h$^{-1}$, respectively

• Nanoaerosols (< 100 nm) are generally the most numerous in the ReNEWW House
"You know what I am? I'm a dust magnet!"¹

Chamber measurements: aerosols and microbes

• Real carpets borrowed from friends & colleagues
• 4 kg simplified mechanical crawling infant
• Phase I: fluorescent biological aerosol particles (FBAPs) & microbes (qPCR/NGS)
  – 5 carpets, 50 resuspension experiments
  – BioScout, optical particle sizer, IOM and PM$_{2.5/10}$ samplers, settled dust collection
  – infant crawling vs. adult walking (as reference)
• Phase II: mechanistic analysis
  – 12 carpets, 108 resuspension experiments
  – spatial variation: dust to near-floor region to bulk air
  – multi-zone material balance model
Particle resuspension dynamics in infant near-floor microenvironments: 

phase I and phase II

(I) real-time *bio*PM concentrations and size distributions in infant & adult breathing zone (BZ)

(I) infant crawling vs. adult walking

(II) vertical variation in resuspended particle concentrations: near-floor vs. bulk air

(II) impact of vacuuming on resuspension

(I) size-resolved *bio*PM Respiratory Tract Deposited Dose Rates (RTDDR)

(I) DNA-based analysis of resuspended microbes (qPCR/NGS)

(II) size-resolved resuspension fractions/rates, emission rates

(II) size-resolved intake fractions
Crawling simulator – baby bot!
Real-time monitoring of resuspended bioPM via laser-induced fluorescence (LIF)

<table>
<thead>
<tr>
<th>LIF instrument</th>
<th>Particle size range (μm)</th>
<th>Excitation wavelength ($\lambda_{ex}$, nm)</th>
<th>Emission wavelength ($\lambda_{em}$, nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BioScout</td>
<td>0.5-15.4</td>
<td>405</td>
<td>&gt; 442</td>
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<tr>
<td>WIBS</td>
<td>0.5-50</td>
<td>280, 370</td>
<td>310-400, 420-650</td>
</tr>
<tr>
<td>UV-APS</td>
<td>0.5-15</td>
<td>355</td>
<td>430-580</td>
</tr>
</tbody>
</table>
Material balance model for linking settled dust, near-floor region & bulk air

Zone 1: Settled Dust (SD)
- $L_{SD,j}$
- $A$
- $A_a$

Zone 2: Near-Floor (NF)
- $Q_{NF}$
- $C_{NF,j}$
- $iF_j$
- $\Phi_j$
- $V_{NF}$
- $f$
- $\beta_{NF,j}$
- $r_j$

Zone 3: Bulk Air (BA)
- $C_{BA,j}$
- $V_{BA}$
- $\beta_{BA,j}$

$C_{Out,j}$

$Q_{BA}$

$Q_{BA}$
Resuspension = transient bioPM emission & exposure scenario

Crawl – Infant BZ

10 min. bkg., no crawl

20 min.

15 min. decay, no crawl

Crawling path – resuspension sequence

BioScout in infant BZ

FBAP size distributions

Total particle size distributions

Size-integrated FBAPs

FBAPs: 2–4 cm$^{-3}$

Minute-to-minute fluctuations in concentrations

Burst of FBAPs at onset of crawling – rapid decay after movement ends: majority of exposure will likely occur during active periods of movement
Resuspension = transient \textit{bio}PM emission & exposure scenario

FBAP size distributions

total particle size distributions

size-integrated FBAPs

walking path – resuspension sequence
BioScout in adult BZ

gradual rise in FBAP concentrations – enhanced mixing of chamber air

nearly steady-state concentrations after ~10 min.
Crawling vs. walking – how do they compare?

FBAP number size distributions (#/cm³)

- Prominent 3-5 μm mode, consistent across carpets: likely bacterial cell agglomerates
- Roughly 10X variation across 5 carpets
- Super-10 μm mode: multicellular fungal spores, pollen grains, abiotic bioPM carrier particles, squames, fabric fibers
- Minimal resuspension of sub-1 μm FBAPs
Infants are exposed to ~50 to 600 μg/m³ of resuspended FBAPs

Resuspension as near-continuous supply of bioPM to the BZ: each bar is a sequential 20 min. resuspension period – little to no decrease in FBAP concentrations
Much of the resuspended bioPM is deposited in the tracheobronchial + pulmonary regions of the infant respiratory system: 1,000 to 10,000 FBAPs deposit in airways per minute!

**FBAP Number Respiratory Tract Deposited Dose Rates:** how many bioPM deposit in each region of the respiratory system per unit time crawling or walking.

determined via integration of FBAP BZ size distributions, age-specific lung deposition fractions, breathing parameters, and hygroscopic bioPM growth in lungs.
PM sampling in the middle of a room? You’ll under-estimate infant exposure by ~ factor of 10!

vertical variation generally becomes more pronounced with increasing particle size, as settling velocity and deposition rate increase
Impact of vacuuming on bioPM resuspension

two frieze carpets, very different results

efficacy of vacuuming in reducing resuspension and exposure is inversely related to particle size
Improving the physical characterization of house dust –
particle number size distributions

32 dust samples: laser-diffraction measurement w/ PAMAS SVSS

the dust size distribution 
(dL/dlogD_p) is a key input in material-balance models to 
determine the resuspension 
fraction

generally, as dust load (mass) 
increases, greater number of 
particles per size fraction 

size distributions vary by ~ two 
orders of magnitude!

greater number of sub-1 μm particles in carpet 
dust, although small contribution to mass

a square meter of carpet can 
contain 1 to 100 billion particles!
Crawling infants can resuspend \( \sim 0.05 \) to 0.4 mg of settled dust per minute!

Particle mass emission rates ↑ with ↑ particle size: larger particles are easier to detach.
Intake fractions: ratio of # of particles inhaled to those that resuspend

Intake fractions range from 5,000 to 10,000 inhaled particles per million that resuspend.

Intake fractions ↑ with ↓ particle size. why? greater loss rates for larger particles.
Conclusions (what we know for sure: babies are mini Pig-Pens)

• Resuspension of bioPM from carpet dust represents a (major?) source of bioPM in the infant BZ, with emission rates ranging from ~0.05 to 0.4 mg per minute and increasing with particle size

• Improved exposure assessment w/ real-time, size-resolved BZ monitoring via laser-induced fluorescence: capture transient dynamics of bioPM resuspension

• Concentrated cloud of particles around crawling infants: greater than bulk air by X10

• Infants receive much of their inhaled dose in their lower airways

• 1,000 to 10,000 bioPM deposit in respiratory system per minute crawling or walking

• Vacuuming can reduce, but not eliminate microbial exposures

• Resuspension = good or bad? microbial + allergenic vs. SVOCs/metals/etc. exposures?
Thank You!

Any Questions?

e-mail: bboor@purdue.edu
Twitter: @BrandonBoor