Natural Ventilation: Theory
Hal Levin
Natural Ventilation: Theory

Definitions
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

Natural and Mixed Mode Ventilation Mechanisms

Natural Ventilation
- Cross Flow Wind
- Wind Tower
- Stack (Flue)
- Stack (Atrium)

Mixed Mode Ventilation
- Fan Assisted Stack
- Top Down Ventilation
- Buried Pipes

Courtesy of Martin Liddament via Yuguo Li
Climate Typology (oversimplified!)
Not in handout materials – to be completed by class

<table>
<thead>
<tr>
<th>Climate type</th>
<th>Diurnal swing</th>
<th>Steady daily cycle</th>
<th>Seasonal variation</th>
<th>No seasonal variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot humid</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot dry</td>
<td>Low desert</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperate humid</td>
<td></td>
<td>London</td>
<td>Milan, Italy</td>
<td></td>
</tr>
<tr>
<td>Temperate dry</td>
<td>High desert</td>
<td></td>
<td></td>
<td>Quito, Ecuador</td>
</tr>
<tr>
<td>Temperate seasonal -- Temp</td>
<td>Boston</td>
<td>Lima</td>
<td>Montreal, Canada</td>
<td></td>
</tr>
<tr>
<td>Temperate seasonal – RH</td>
<td>San Francisco</td>
<td>Lima</td>
<td>Montreal, Canada</td>
<td></td>
</tr>
<tr>
<td>Cold humid</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold dry</td>
<td>Bogotá</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 either 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)

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

#### Isolation room ventilation
Goal: ~12 ach or 160 l/s-p (?)

![Diagram of isolation room ventilation](image)

- Suspended ceilings
- Corridor
- Anteroom
- Cubicle
- Toilet/bathroom

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
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 -- **Buoyancy**

**Stack effect**

Hot air = buoyancy
Natural driving mechanisms -- **Buoyancy**

**Stack effect**

Applications: Supply of outdoor air

- Supply of outdoor air … removal of pollutants
  - In air changes per hour (AER or h⁻¹) or liters per person per second (l/s-p)
  - What happens if you have a very tall space?
- Pollutant concentration = source strength/removal rate
  - Removal rate includes dilution/exhaust plus deposition on surfaces or chemical interactions/transformation
  - Chemicals: source strength expressed as mg of pollutant / m²-h or mg/h
  - Dilution/exhaust rate expressed as dilution ventilation (air changes per hour)
  - Deposition: g cm⁻¹ s⁻¹
Pollutant concentration as a function of outdoor air exchange rate

Applications: Convective cooling

- **convection** /kon-vek-shun/ (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 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

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
Physiological cooling

Impact of wind and temperature difference on natural ventilation
Concept of the neutral level

External pressure gradient

Internal pressure gradient

Neutral plane

Single-sided ventilation

Cross flow ventilation takes place through internal leakage paths or internal doors

(a) Single sided unsealed enclosure
Influence of wind and temperature (stack effect) on ventilation and air flow pattern

Cross flow ventilation

(source: AIVC, 2009)
Stack ventilation (dwellings)
(source: AIVC 2009)

Stack ventilation (atrium)
(source: AIVC 2009)
**Stack driving flows in a building**

(A) Indoor air warmer than outdoor

(B) Indoor air cooler than outdoor

Stack effect

Stack effect in a high rise building
Liberty Tower, Meiji University, Tokyo
Meiji University Liberty Tower, Tokyo, Japan
(source: Professor Toshihara Ikaga, Keio University)

Wind Floor for Hybrid Ventilation

Gross Floor Area: 59000 m² completed in 1998

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

Table 3.1. 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**

\[ Q = C J \left( \frac{\varepsilon T^2}{1 + \varepsilon / (\varepsilon + \varepsilon_{\text{ref}})} \right) \frac{\Delta T \Delta H}{T} \]

\( \varepsilon = \frac{A1}{A2}, \ \frac{T}{A1}, \ A1 = A2 \)

where \( C_J \) is the discharge coefficient

(c) **Ventilation due to temperature difference with one opening**

\[ Q = C_J \frac{A}{3} \frac{\Delta T \Delta H}{T} \]

http://books.google.com/books?hl=en&lr=&id=1tdQMyhPA2gC&oi=fnd&pg=PR9&dq=Natural+ventilation+theory&ots=mFzmfd4mct&sig=XA3zksH_OBkkS8IILbxmwJgbWyo

Table 3.2. Formulae for cross ventilation [1]

(a) **Ventilation due to wind only**

\[ Q = C_J A \sqrt{\frac{M_C}{P}} \]

\[ \frac{1}{A} = \frac{1}{(A_1 + A_2) / (A_1 + A_2)} \]

(b) **Ventilation due to temperature difference only**

\[ Q = C_J A \left( \frac{2\Delta T \Delta H}{T} \right)^{1/2} \]

\[ \frac{1}{A} = \frac{1}{(A_1 + A_2) / (A_1 + A_2)} \]

\[ T = T_1 = T_2 \]

(c) **Ventilation due to wind and temperature difference**

\[ Q = Q_0 \text{ for } \frac{V}{\Delta T} < 0.26 \frac{A_1 H_1}{A_2 M_C P} \]

\[ Q = Q_0 \text{ for } \frac{V}{\Delta T} > 0.26 \frac{A_1 H_1}{A_2 M_C P} \]

\[ \Delta T = T_1 - T_2 \]
Indoor air velocities for naturally ventilated spaces under different wind directions and different number of apertures and locations

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Width of aperture/width of wall = 0.66</th>
<th>Width of aperture/width of wall = 1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( V_{in} ) (%)</td>
<td>( V_{out} ) (%)</td>
</tr>
<tr>
<td>Single aperture in windward wall, wind direction perpendicular</td>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td>Single aperture in windward wall, wind direction at an angle</td>
<td>15</td>
<td>23</td>
</tr>
<tr>
<td>Single aperture in leeward wall, wind direction at an angle</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>Two apertures in leeward wall, wind direction at an angle</td>
<td>22</td>
<td>23</td>
</tr>
<tr>
<td>One aperture in windward wall, another in adjacent wall, wind direction perpendicular to inlet</td>
<td>45</td>
<td>51</td>
</tr>
<tr>
<td>One aperture in windward wall, another in adjacent wall, wind direction at an angle</td>
<td>37</td>
<td>40</td>
</tr>
<tr>
<td>One aperture in windward wall, another in leeward wall, wind direction perpendicular to inlet</td>
<td>35</td>
<td>37</td>
</tr>
<tr>
<td>One aperture in windward wall, another in leeward wall, wind direction at an angle</td>
<td>42</td>
<td>42</td>
</tr>
</tbody>
</table>

Effects of inlet / outlet sizes in cross-ventilated spaces with openings on opposite walls

Figure 3.1. Effects on inlet and outlet sizes in cross-ventilated spaces with openings on opposite walls
Velocity as percent of wind velocity: openings on opposite walls, wind perpendicular to inlet

Table 3.5. Effect of inlet and outlet sizes in cross-ventilated spaces; openings on opposite walls; wind perpendicular to inlet [11]

<table>
<thead>
<tr>
<th>Conditions for perpendicular winds</th>
<th>( V_{\text{in}} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width inlet/Width of wall = 1/3 and Width outlet/Width of wall = 1/3</td>
<td>35</td>
</tr>
<tr>
<td>Width inlet/Width of wall = 1/3 and Width outlet/Width of wall = 2/3</td>
<td>39</td>
</tr>
<tr>
<td>Width inlet/Width of wall = 1/3 and Width outlet/Width of wall = 1</td>
<td>44</td>
</tr>
<tr>
<td>Width inlet/Width of wall = 2/3 and Width outlet/Width of wall = 1/3</td>
<td>34</td>
</tr>
<tr>
<td>Width inlet/Width of wall = 2/3 and Width outlet/Width of wall = 2/3</td>
<td>37</td>
</tr>
<tr>
<td>Width inlet/Width of wall = 2/3 and Width outlet/Width of wall = 1</td>
<td>35</td>
</tr>
<tr>
<td>Width inlet/Width of wall = 1 and Width outlet/Width of wall = 1/3</td>
<td>32</td>
</tr>
<tr>
<td>Width inlet/Width of wall = 1 and Width outlet/Width of wall = 2/3</td>
<td>36</td>
</tr>
<tr>
<td>Width inlet/Width of wall = 1 and Width outlet/Width of wall = 1</td>
<td>47</td>
</tr>
</tbody>
</table>

Effect of oblique wind direction with openings on opposite walls

Figure 3.2. Openings on opposite walls; wind oblique to inlet
Velocity as percent of wind velocity: Openings on opposite walls, wind oblique to inlet

Table 3.6. Effect of inlet and outlet sizes in cross-ventilated spaces; openings on opposite walls; wind oblique to inlet [11]

<table>
<thead>
<tr>
<th>Conditions for oblique to inlet winds</th>
<th>$V_{in} (%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width inlet/Width of wall = 1/3 and Width outlet/Width of wall = 1/3</td>
<td>42</td>
</tr>
<tr>
<td>Width inlet/Width of wall = 1/3 and Width outlet/Width of wall = 2/3</td>
<td>40</td>
</tr>
<tr>
<td>Width inlet/Width of wall = 1/3 and Width outlet/Width of wall = 1</td>
<td>44</td>
</tr>
<tr>
<td>Width inlet/Width of wall = 2/3 and Width outlet/Width of wall = 1/3</td>
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<tr>
<td>Width inlet/Width of wall = 2/3 and Width outlet/Width of wall = 2/3</td>
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<td>Width inlet/Width of wall = 2/3 and Width outlet/Width of wall = 1</td>
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<td>Width inlet/Width of wall = 1 and Width outlet/Width of wall = 1/3</td>
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<td>Width inlet/Width of wall = 1 and Width outlet/Width of wall = 2/3</td>
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<tr>
<td>Width inlet/Width of wall = 1 and Width outlet/Width of wall = 1</td>
<td>65</td>
</tr>
</tbody>
</table>

Effects of inlet / outlet sizes in cross-ventilated spaces, openings on adjacent walls

Wind perpendicular

Wind oblique
Effect of inlet and outlet sizes, openings on adjacent walls, wind perpendicular to inlet

Table 3.7. Effect on inlet and outlet sizes in cross-ventilated spaces; openings on adjacent walls; wind perpendicular to inlet \([11]\)

<table>
<thead>
<tr>
<th>Conditions for perpendicular to inlet winds</th>
<th>(V_{eq} (%))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width inlet/Width of wall = 1/3 and Width outlet/Width of wall = 1/3</td>
<td>45</td>
</tr>
<tr>
<td>Width inlet/Width of wall = 1/3 and Width outlet/Width of wall = 2/3</td>
<td>39</td>
</tr>
<tr>
<td>Width inlet/Width of wall = 1/3 and Width outlet/Width of wall = 1</td>
<td>51</td>
</tr>
<tr>
<td>Width inlet/Width of wall = 2/3 and Width outlet/Width of wall = 1/3</td>
<td>51</td>
</tr>
<tr>
<td>Width inlet/Width of wall = 1 and Width outlet/Width of wall = 1/3</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 3.8. Effect on inlet and outlet sizes in cross-ventilated spaces; openings on adjacent walls; wind oblique to inlet \([11]\)

<table>
<thead>
<tr>
<th>Conditions for oblique to inlet winds</th>
<th>(V_{eq} (%))</th>
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</thead>
<tbody>
<tr>
<td>Width inlet/Width of wall = 1/3 and Width outlet/Width of wall = 1/3</td>
<td>37</td>
</tr>
<tr>
<td>Width inlet/Width of wall = 1/3 and Width outlet/Width of wall = 2/3</td>
<td>40</td>
</tr>
<tr>
<td>Width inlet/Width of wall = 1/3 and Width outlet/Width of wall = 1</td>
<td>45</td>
</tr>
<tr>
<td>Width inlet/Width of wall = 2/3 and Width outlet/Width of wall = 1/3</td>
<td>36</td>
</tr>
<tr>
<td>Width inlet/Width of wall = 1 and Width outlet/Width of wall = 1/3</td>
<td>37</td>
</tr>
</tbody>
</table>

Simple formulation for Vent Calculation

\[ Q = \left(\frac{K}{A}\right) \cdot V \]

- \(Q\) = cfm/hr
- \(V\) = Wind mph
- \(A\) = Area of Inlet
- \(K\) = Outlet to Inlet Variable

[Diagram showing positive and negative pressure on inlet and outlet with wind direction and relationship to area and flow.]
How to use natural ventilation to cool narrow office buildings

E. Grazia, J. Bruyère, A. De Herde

Fig. 7. Climatic data of the sunny summer day.

**Single-sided ventilation**

Air exchange takes place through stack action and/or differences in wind pressure

- Multi or large opening sealed single sided
Natural and Mixed Mode Ventilation Mechanisms

- **Natural Ventilation**
  - Cross Flow Wind
  - Wind Tower
  - Stack (Flue)
  - Stack (Atrium)

- **Mixed Mode Ventilation**
  - Fan Assisted Stack
  - Top Down Ventilation
  - Buried Pipes

Air exchange is driven by turbulent fluctuations. Ventilation rates can be very small unless openings are large.

(Images of ventilation mechanisms)

Courtesy of Martin Liddament via Yuguo Li
Natural Ventilation Issues

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

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.

Chapter 2.
Global ambient air pollution concentrations and trends

Bjarne Sivertsen

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

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

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

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

Pollutant concentrations by national level of development

Fig. 3. Typical annual average concentrations of nitrogen dioxide, sulfur dioxide and suspended particles in different parts of the world

Source: United Nations Human Settlements Programme (5)
## U.S. EPA National Ambient Air Quality Standards (NAAQS) [http://www.epa.gov/air/criteria.html](http://www.epa.gov/air/criteria.html)

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Primary Standards</th>
<th>Secondary Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Level</td>
<td>Averaging Time</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>9 ppm (1.0 mg/m³)</td>
<td>8-hour [11]</td>
</tr>
<tr>
<td></td>
<td>55 ppm (40 mg/m³)</td>
<td>1-hour [11]</td>
</tr>
<tr>
<td>Lead</td>
<td>0.15 μg/m³ [2]</td>
<td>Rolling 3-Month Average</td>
</tr>
<tr>
<td></td>
<td>1.5 μg/m³</td>
<td>Quarterly Average</td>
</tr>
<tr>
<td>Nitrogen Dioxide</td>
<td>0.050 ppm (100 μg/m³)</td>
<td>Annual (Arithmetic Mean)</td>
</tr>
<tr>
<td>Particulate Matter (PM₁₀)</td>
<td>150 μg/m³</td>
<td>24-hour [12]</td>
</tr>
<tr>
<td>Particulate Matter (PM₂.₅)</td>
<td>15.0 μg/m³</td>
<td>Annual [20] (Arithmetic Mean)</td>
</tr>
<tr>
<td></td>
<td>50 μg/m³</td>
<td>24-hour [2]</td>
</tr>
<tr>
<td>Ozone</td>
<td>0.075 ppm (2006 std)</td>
<td>8-hour [6]</td>
</tr>
<tr>
<td></td>
<td>0.08 ppm (1997 std)</td>
<td>8-hour [12]</td>
</tr>
<tr>
<td></td>
<td>0.12 ppm</td>
<td>1-hour [11]</td>
</tr>
<tr>
<td>Sulfur Dioxide</td>
<td>0.03 ppm (Annual (Arithmetic Mean))</td>
<td>0.5 ppm (1500 μg/m³)</td>
</tr>
<tr>
<td></td>
<td>0.14 ppm</td>
<td>24-hour [12]</td>
</tr>
</tbody>
</table>

## Average annual PM₁₀ concentrations in selected cities world wide (part 1)

Sources: Bourret et al. [7]; US Environmental Protection Agency [8]; Sivertsen & El Seoud [9]; Sivertsen et al. [10]; State Environmental Protection Agency [11]; CAFE [12]; Department of Environment and Heritage [13]; Department of Environmental Affairs and Tourism [14]; US Environmental Protection Agency [15].
Average annual PM$_{10}$ concentrations in selected cities world wide (part 2)

Average annual PM$_{10}$ concentrations in selected cities world wide (part 3)
Average annual PM$_{10}$ concentrations in selected cities world wide (part 4)

**NORTH AMERICA**

Average annual PM$_{10}$ concentrations in selected cities world wide (part 5)
Average annual PM$_{10}$ concentrations in selected cities world wide (part 6)

Europe
Ultrafine particle number concentrations measured in urban and roadside environments

Table 2. Ultrafine particle number concentrations measured in urban and roadside environments

<table>
<thead>
<tr>
<th>Location</th>
<th>Monitoring period</th>
<th>Average particle number concentration per cm²</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barcelona, Spain</td>
<td>Not stated</td>
<td>$1.23 \times 10^4$</td>
<td>Paatero et al. (28)</td>
</tr>
<tr>
<td>Birmingham, England</td>
<td>Not stated</td>
<td>$1.8 \times 10^5$ road/kit</td>
<td>Harrison et al. (29)</td>
</tr>
<tr>
<td>Brisbane, Australia</td>
<td>14–29 January 2004</td>
<td>$\sim 2.7 \times 10^6$ ins/disk</td>
<td>Holmes et al. (33)</td>
</tr>
<tr>
<td>Brisbane, Australia</td>
<td>1995 – April 1997</td>
<td>7.4 $\times 10^7$ urban</td>
<td>Morawska et al. (34)</td>
</tr>
<tr>
<td>Copenhagen, Denmark</td>
<td>3–20 May 1999</td>
<td>$1.2 \times 10^3$ – $2.0 \times 10^5$ ins/disk</td>
<td>Wühl et al. 2001 (52)</td>
</tr>
<tr>
<td>Detroit, USA</td>
<td>July 2002</td>
<td>$1.0 \times 10^5$ ins/disk</td>
<td>Young &amp; Kaofer (38)</td>
</tr>
<tr>
<td>Erfurt, Germany</td>
<td>1991–2001</td>
<td>$1.04 \times 10^6$ – $1.4 \times 10^7$ ins/disk</td>
<td>Kreyling et al. (34)</td>
</tr>
<tr>
<td>Helsinki, Finland</td>
<td>1999–2001</td>
<td>$1.90 \times 10^7$ ins/disk</td>
<td>Hussain et al. (35)</td>
</tr>
<tr>
<td>Los Angeles, USA</td>
<td>Aug–Oct 2001</td>
<td>$6.00 \times 10^6$ ins/disk</td>
<td>Zhu et al. (36)</td>
</tr>
<tr>
<td>Rome, Italy</td>
<td>Not stated</td>
<td>$1.8 \times 10^7$ – $3.5 \times 10^7$ road/kit</td>
<td>Paatero et al. (28)</td>
</tr>
</tbody>
</table>

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

Wind: direction and velocity are neither stable nor consistent

- 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.
- Relying on wind alone can result in both under and over-ventilation relative to a design objective.
Lima, Peru: May 1, 2008

Lima, Peru: September 1, 2008
Grantham Hospital Study, Hong Kong
Yuguo Li

(A)

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
Natural Ventilation: Theory

References


