Implication of Urban Heating on Pollutant Concentration: Urban Canopy Air Quality and Breathability

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Outline

• Introduction
  • Background
  • Objective and Motivations

• Methods
  • Model Description and Numerical Settings
  • Simulation Set-up
  • Time-space averaging

• Characterization of Unstable Flow Field
  • Diurnal Non-uniform Heating of Urban Surfaces
  • Momentum Versus Buoyancy Forcing
  • Diurnal variation of Horizontal and Vertical Richardson Numbers

• Results
  • Flow and dispersion fields
  • Breathability in Urban Street Canyons

• Summary and Conclusion
### Introduction and Background

#### Pollutant Concentration

- Emission

#### State of the Atmosphere

- Local Ambient Condition
- Roughness Morphology
- Thermal Stratification

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*Sini et al. 1996*

“The differential heating of street surfaces largely influences the transport and pollutants exchange.”
Objectives and Motivations

1. How to improve the CFD simulations of street-scale urban environment?

**COMPREHENSIVE:**
- Indoor-Outdoor building energy model, flow field, and pollutant dispersion,
- Solar load, soil layers and realistic wind and temperature profiles.

**REALISTIC:**
- Three-dimensional realistic and transient heating due to solar radiation and shading,
- 3-D compact mid-rise urban industrial/residential zones with low vegetation.

**ADVANCED NUMERICAL MODELING:**
- Large Eddy Simulation model and validation against experimental data.

2. How to comprehensively characterize the street canyon under unstable conditions? What are the factors that modify this characterization? Validity?

3. How do the flow, temperature and dispersion fields correlate with this characterization method?
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Model Description

**TUF-IOBES**

“Temperature of Urban Facets, Indoor-Outdoor Building Energy Simulator”
- Real weather conditions
- Building and urban material properties
- Composition of the building envelope (e.g. windows, insulation)
- Waste heat from air-conditioning systems
- Indoor heat sources

**PALM**

“The PArallelized Large-eddy simulation Model (PALM)”
- The Filtered, incompressible Boussinesq equations
  - The 1st law of thermodynamics
- The subgrid-scale (SGS) turbulent kinetic energy (TKE) equation
  - Passive scalar (pollutant) equation

Simulation Setup

**Figure 1- Schematic of the computational domain**

<table>
<thead>
<tr>
<th><strong>Computational Domain</strong></th>
<th>Matrix of 5x3 Cuboid buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Simulation Site</strong></td>
<td>Boston, Massachusetts Latitude of 42° July 6-8th Average daily temperature</td>
</tr>
<tr>
<td><strong>Configuration</strong></td>
<td>H/W=1 ( \lambda_p = 0.29, \lambda_f = 0.25 )</td>
</tr>
<tr>
<td><strong>Albedo</strong></td>
<td>0.1 (ground) – 0.3 (walls)</td>
</tr>
<tr>
<td><strong>Wind Direction</strong></td>
<td>( \theta = 0° ) from EW</td>
</tr>
<tr>
<td><strong>Wind Speed</strong></td>
<td>( U_b = 0.5, 1, 2, 3 ) m s(^{-1})</td>
</tr>
</tbody>
</table>
LES Simulations: Time-Space Averaging Unit

Variability of results in spanwise direction

- Coceal et al 2007 – DNS simulation of flow over a matrix of cubes
  
  “Roll Like circulations with axes in the streamwise direction”
  
  “Statistics should be collected over 200-400 large eddy turn over time”

**Figure 2** - Contour plots of streamwise velocity \( \frac{u}{U_b} \)  
30 minutes averaged results

**Figure 3** - Contour plots of streamwise velocity \( \frac{u}{U_b} \)  
averaged over 11hrs

LES Simulations: Time-Space Averaging Unit

Ensemble-averaging statistics over the repeating units to improve the effective averaging time.

Figure 4 - sub domain unit as shown by the red square. The total domain consist of 5*3 times the subdomain.

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Diurnal Non-Uniform Heating of Urban Surfaces

- Clear Summer Day at Latitude of 42 degree

Buoyancy and Momentum Forcing

- Two different Richardson numbers are defined to characterize the flow at different time of the day (ToD).
- $Ri_v$ indicates the vertical atmospheric stability and $Ri_h$ is the measure for wall heating orientation and strength.

**Gradient Ri Number**

\[
Ri_v = \left( \frac{g H}{R_i b} \right) \frac{T_H - T_a}{T_a \frac{\partial T}{\partial z} \frac{\partial U}{\partial z}}
\]

\[
Ri_h = \frac{g \frac{\partial T}{\partial x} \frac{\partial U}{\partial z}^2}{T \frac{\partial V}{\partial z}} \approx \frac{U_b}{H}^2 = \frac{U_b}{H}^2
\]

**Bulk Ri Number**

\[
= \left( \frac{Ri_h}{R_i b} \right) \frac{T_W - T_L}{T_a} \left[ \frac{Q}{\Delta T (\Delta U)^2 + (\Delta V)^2} \right]
\]

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Diurnal Variation of Richardson Numbers

\[ Ri_v = \left( \frac{gH}{U_b^2} \right) \frac{T_H - T_g}{T_a} \]

\[ Ri_h = \frac{g \frac{\partial T}{\partial x}}{\left( \frac{\partial U}{\partial z} \right)^2} \approx \left( \frac{gH}{U_b^2} \right) \frac{T_W - T_L}{T_a} \left( \frac{H}{W} \right) \]

- **AC** – Assisting Condition - \( Ri_h < 0 \)
- **HH** – Horizontal Heating - \( Ri_h \approx 0 \)
- **OC** – Opposing Condition - \( Ri_h > 0 \)

\[ U_b = 0.5 \text{ m/s} \]

\[ \begin{array}{cccc}
AC1 & AC2 & HH & OC \\
0930 & 1100 & 1330 & 1600 \\
-19.2 & -54.5 & -77.5 & -53.6 \\
-32.7 & -23.4 & 0 & 22.5 \\
\end{array} \]
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Results

• PART 1 - FLOW FIELD and DISPERSION
  Contour plots of flow, temperature and concentration
  Vertical Profile of turbulent fluxes at different locations

• PART 2 - Air Quality and Breathability
  Pollutant concentration at pedestrian level
  Air Exchange Rate and Pollutant Exchange Rate
Flow Field and Dispersion

Contour plots of normalized mean velocity magnitude, temperature and concentration field

**Horizontal Heating (1330EDT),** $Ri_h=0$, Max $Ri_v$

- AR=1
- *Vertical* plane in the center of building canyon
- *Time-Ensemble Averaged* for 1800s and 15 subdomain units
- $Ub=0.5, 1, 2, 3 \text{ m/s}$

\[
C^+ = \frac{C - C_{ref}}{E \cdot H / U_b}
\]

\[
T^+ = \frac{T - T_{ref}}{Q_h / U_b}
\]
Flow Field and Dispersion

Contour plots of normalized mean velocity magnitude, temperature and concentration field

- **Diurnal Variation of Surface Heating**
- **AR=1**
- **Vertical** plane in the center of building canyon
- **Time-Ensemble Averaged** for 1800s and 15 subdomain units
- **Ub=0.5 m/s**
## Flow Field and Dispersion

Contour plots of normalized mean velocity magnitude, temperature and concentration field:
- **Diurnal Variation of Surface Heating**
- **AR=1**
- **Vertical** plane in the center of building canyon
- **Time-Ensemble Averaged** for 1800s and 15 subdomain units
- **Ub=3m/s**

<table>
<thead>
<tr>
<th></th>
<th>AC1</th>
<th>AC2</th>
<th>HH</th>
<th>OC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ri&lt;sub&gt;h&lt;/sub&gt;</td>
<td>-0.9, Ri&lt;sub&gt;v&lt;/sub&gt; = -0.5</td>
<td>-0.6, Ri&lt;sub&gt;v&lt;/sub&gt; = -1.5</td>
<td>0.1, Ri&lt;sub&gt;v&lt;/sub&gt; = -2.1</td>
<td>0.6, Ri&lt;sub&gt;v&lt;/sub&gt; = -1.4</td>
</tr>
</tbody>
</table>

Diagrams showing:
- **U<sup>+</sup>** normalized mean velocity magnitude
- **T<sup>+</sup>** temperature
- **C<sup>+</sup>** concentration field
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Breathability in Urban Street Canyons

\[ U_b = 3 \text{ m/s} \]

- **Volum Average (Spanwise Canyon)**
- **Pedestrian level \( (z=2\text{m}) \)**

![Graph showing dimensionless concentration vs. Ri_n vs. time (hr)]
Breathability in Urban Street Canyons

- $U_b = 0.5 \text{ m/s}$
- $U_b = 1 \text{ m/s}$
- $U_b = 2 \text{ m/s}$
- $U_b = 3 \text{ m/s}$
Conclusion and Summary

**Project Goal:**
- A realistic and comprehensive study of urban microclimate with LES modeling
- Time and spatial averaging is combined for more accurate representation of flow statistics

**Comprehensive characterization Method:**
- Break down of the total thermal forcing in urban environments into directional forcings indicated by $Ri_h$ and $Ri_v$, that are modified by surface material and radiative properties as well as wind speed and direction
- Validity of characterization method evaluated by a similarity analysis

**Breathability in the Urban Canyon Under Unstable Stratification**

Modification of flow field by the horizontal heating is more apparent for a strongly unstable condition

Thermal field is strongly correlated with the sign of $Ri_h$

Dispersion field changes linearly as a function of $1/Ri_v$, except for cases of high $Ri_h$ to $Ri_v$ ratio
Validation of numerical models

- Velocity and temperature field of PALM validated by Park et al. [1]
- The prognostic equation for passive scalars in PALM validated by Park et al. [5]
3-Dimensional Air Exchange Rate (ACH)

The effect of non-uniform heating on the air removal performance of street canyon

\[
ACH = ACH_{\text{top}} + ACH_{\text{side}}
\]

\[
ACH_{\text{top}} = \frac{\iint <w> \, dx \, dy}{A_{\text{top}}}
\]

\[
ACH_{\text{side}} = \frac{\iint <v_{\pm}> \, dz \, dy}{A_{\text{side}}}
\]
3-Dimensional Air Exchange Rate (ACH)

- The effect of non-uniform heating on the air removal performance of street canyon

![Graph showing 3-Dimensional Air Exchange Rate (ACH)]