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LARGE-EDDY SIMULATION OF POLLUTANT PLUME DISPERSION OVER 2D IDEALIZED STREET CANYONS

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OUTLINE

- Introduction
- Methodology
- Results & Discussion
  - Pollutant transport below and around roof level
  - Pollutant dispersion in the urban boundary layer (UBL)
INTRODUCTION

In a developed city like Hong Kong, the building-height-to-street-width ratio (aspect ratio, AR) is large. In case the wind is flowing perpendicular to the street canyon (worst case), the flow falls into skimming flow regime in which flesh air cannot entrain into the street canyons by mean flow.

A satellite photo of Mong Kok, Hong Kong

Any methods to remove/dilute the pollutants better?

Source: Google map
OBJECTIVES

The core objectives of this study are:

- Develop a platform to calculate pollutant dispersion over idealized 2D street canyons using LES.

- Examine how 2D urban roughness affects the flow structure and the pollutant dispersion in the urban boundary layer (UBL).

- Elucidate the pollutant removal mechanism when the prevailing flow is perpendicular to the street canyons.
Currently, three types of models are commonly used for resolving/modeling fluid turbulence.

- $k$-$\varepsilon$ model (RANS based)
- Large-eddy simulation (LES)
- Direct numerical simulation (DNS)

**Accuracy**
- Lower
- Relatively cheap
- Expensive
- Higher
- Very expensive

**Computational cost**
THE REASON OF USING LES

- Pollutant dispersion is strongly correlated with atmospheric turbulence
  - $k-\varepsilon$ model assumes isotropic turbulent kinetic energy (TKE) but the turbulence structure over 2D roughness is highly anisotropic

- Study of turbulence structure of individual components (i.e.: stream-wise fluctuation component) could not be achieved using $k-\varepsilon$ turbulence model.
METHODODOLOGY

- Computational domain and boundary conditions

- Inlet: periodic; zero pollutant
- Top boundary: symmetry
- Outlet: periodic; open boundary for pollutant

AR (Aspect ratio) = h/b

AR = 0.25

AR = 1.0
MODEL DETAILS

- CFD code used: OpenFOAM 1.7.0

- Turbulence model: Large-eddy simulation
  - With One-equation TKE subgrid-scale (SGS) model

- Velocity-pressure coupling: PISO

- Reynolds number: ~10,000

- Pollutant source: Constant concentration source
# List of Completed Computations

<table>
<thead>
<tr>
<th>Model</th>
<th>AR = 1</th>
<th>AR = 1 (Coarse)</th>
<th>AR = 0.25</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of canyons</td>
<td>12</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>No. of grids in each canyon (x,y,z)</td>
<td>32x160x32</td>
<td>16x80x16</td>
<td>128x160x32</td>
</tr>
<tr>
<td>No. of grids in UBL (x,y,z)</td>
<td>768x160x280</td>
<td>384x80x140</td>
<td>960x160x280</td>
</tr>
<tr>
<td>Total No. of grids</td>
<td>~36M</td>
<td>~4.5M</td>
<td>~47M</td>
</tr>
<tr>
<td>Computation time</td>
<td>5 months</td>
<td>2 months</td>
<td>6 months</td>
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RESULTS & DISCUSSION

Pollutant transport below & around roof level
STREAMLINES

- Primary recirculation is formed within each street canyon.
- The mean wind in the UBL do not go into the street canyons.
Cheng et al. (2008) pointed out that:

In skimming flow regime, the pollutant removal is mainly governed by turbulent transport instead of the mean wind using RANS $k$-$\varepsilon$ turbulence model.
The following slides show the vertical pollutant flux along the roof level. Here, the three types of flux are:

\[
\begin{align*}
\text{Mean flux} &= \langle \bar{w} \rangle \langle \bar{\phi} \rangle / \Phi / U \\
\text{Turbulent flux} &= \langle w'' \phi'' \rangle / \Phi / U \\
\text{Total flux} &= \langle \bar{w} \rangle \langle \bar{\phi} \rangle / \Phi / U + \langle w'' \phi'' \rangle / \Phi / U
\end{align*}
\]

\( \langle \psi \rangle \) is the spatio–temporal average in the spanwise direction. 

\( \psi'' = \psi - \langle \psi \rangle \) is the deviation from its mean.
MEAN FLUX VS TURBULENT FLUX ACROSS ROOF LEVEL (AR=1)

Pollutant removal is dominated by turbulent flux

Pollutant transport is dominated by mean flux
**Mean Flux vs Turbulence Flux Across Roof Level (AR=0.25)**

![Graph showing mean flux vs turbulence flux across roof level with AR=0.25. The graph displays three lines: Total Flux, Turbulence Flux, and Mean Flux.](image-url)
How is the pollutant removed from the street canyons to the UBL?
Some air masses accelerate while most of the air masses decelerate.
**Snap shot of iso-surfaces of streamwise fluctuation velocity at roof level**

- Large amount of decelerating, up-rising air masses are located along the roof level.

\[ u'' < 0 \] represents deceleration.

\[ w'' \approx w \text{ at roof level} \]

\[ \psi'' = \psi - \langle \psi \rangle \text{ is the deviation from its mean.} \]
COHERENT STRUCTURE AT ROOF LEVEL

- $\phi'' < 0$ occurs in the street canyons without pollutant source.

Iso-surface of $u''/U = -0.25$
The accelerating air masses \((u'' > 0)\) carry the background pollutant into the street canyon by sweeps.

The decelerating air masses \((u'' < 0)\) remove the ground-level pollutant to the UBL by ejections.

The primary re-circulation mixes the pollutant within the street canyon.
**Removal Mechanism**

*With* pollutant sources

- Pollutant removal by ejections

*Without* pollutant source

- Pollutant entrainment by sweeps

\[
\text{With pollutant sources} \gg \approx \text{Without pollutant source}
\]
QUESTION

Where does the turbulence come from?
**MEAN FLOW VELOCITY (AR=1)**

The production term of TKE

$$-\frac{1}{2}(u''w'')\times\left(\frac{\partial \bar{u}}{\partial z} + \frac{\partial \bar{w}}{\partial x}\right)$$
RESOLVED-SCALE TKE (AR=1)

Maximum TKE

x/b = -0.4, -0.25, 0.0, 0.25, 0.4
RS-TKE CONTOURS

Maximum TKE

AR=1

AR=0.25

Maximum shear

Local turbulence production is not the major source of roof-level TKE for pollutant removal.
Cui et al. (2004) found that sweeps (u">0, w"<0) dominate the total momentum flux at roof level using LES with street canyon of AR=1.

Christen et al. (2007, pp.1962) figured out that under neutral stratification, sweeps dominate the exchange of vertical momentum at \( z \leq 2.5h \), employing quadrant analysis on the data measured from street canyons in Basel, Switzerland.
SECTION SUMMARY

- The re-circulating flows carry the pollutant to the roof level and also mix/dilute the pollutant within the street canyon.

- The aged air (carrying pollutant) is removed by ejections while fresh air is entrained by sweeps.

- The TKE required for pollutant removal is mainly attributed to the (downward moving) atmospheric turbulence in the UBL.
RESULTS & DISCUSSION

Pollutant dispersion in the UBL
NECESSARY DOMAIN SIZE

- In the LES of open-channel flows over a flat, smooth surface, the domain-length-to-domain-height ratio is often greater than $4\pi$ in order to resolve the turbulence correctly. (e.g. Enstad et al. 2006)

- Its computational cost is too high, if roughness are explicitly resolved.
Two-point Correlation

Two-point correlations are commonly used to determine the necessary (minimum) domain size for resolving the turbulence. Ideally, the correlation of flow velocity drops to zero at certain horizontal separation, which is then used to determine the length scale of turbulence.

\[
R_{uu} = \frac{\langle \overline{u''(x_0)} \overline{u''(x_0 + \delta x)} \rangle}{\sigma_{u(x_0)} \sigma_{u(x_0 + \delta x)}}
\]

- where \( u'' = u - \langle u \rangle_{y,t} \)
TWO-POINT CORRELATION (Ar = 1)

The autocorrelation reaches 0 at any elevations.
TWO-POINT CORRELATION (AR = 0.25)

Two point correlation ($R_{uu}$) for AR = 0.25

Autocorrelation $R_{uu}$

δx/h
STREAMLINES

- The streamlines in the UBL are almost parallel to the streamwise direction.

AR = 0.25

AR = 1.0

Roof level
FLOW FLUCTUATION

![Graphs showing flow fluctuation](image)
**Pollutant Plume**

- **AR = 0.25**

- **AR = 1**
Plume rise

\[ \text{Plume rise} = \frac{\iiint z\phi dydz}{\iiint \phi dzdy} \]
PLUME PROFILES

- Gaussian pollutant plume model has been widely used in the last 5 decades.
  - It was originally designed for rural areas (open terrain).
  - The re-circulating flows below the UBL are not considered

- Davidson et al. (1996), using wind tunnel experiments, showed that the pollutant plume over an obstacle array exhibits a Gaussian form.
**VERTICAL PLUME PROFILE (AR=1)**

\[
\frac{(z-z_{e,\text{max}})}{\sigma_z} = \sqrt{\frac{\int \int z^2 \varphi \, dy \, dz}{\int \int \varphi \, dy \, dz}}
\]
Obvious difference between AR=1 and AR = 0.25
SECTION SUMMARY

- The current computational domain is large enough handling the atmospheric turbulence in the UBL over idealized 2D urban roughness.

- The street canyons of $AR = 0.25$ would have better air quality compared with $AR = 1$ counterparts.

- The vertical plume profiles are functions of ARs.
This study was jointly supported by the Strategic Research Areas and Themes, Computational Sciences, and the University Research Committee Seed Funding Programme of Basic Research 200910159028 of the University of Hong Kong. The computation is supported in part by a Hong Kong UGC Special Equipment Grant (SEG HKU09). The technical support from Lillian Y.L. Chan, Frankie F.T. Cheung, and W.K. Kwan with HKUCC is appreciated.
REFERENCES


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End
Q & A
RESULTS & DISCUSSIONS

Model validation
FLOW STRUCTURE WITHIN CANYON

The vertical profiles of the following parameters on the vertical plane of the model with AR = 1 were investigated:

- Mean flow velocity, u and w
- Turbulence Kinetic Energy, TKE
- Skewness of u and w
- Kurtosis of u and w

The results are compared with LES model by Cheng 2010 (represented by squares), Cui et al. 2004 (represented by triangles) & wind tunnel experiment by Brown 2000 (represented by circles).
**Mean Flow Velocity, \( U \)**

- For various values of \( x/b \):
  - \( x/b = -0.4 \)
  - \( x/b = -0.25 \)
  - \( x/b = 0.0 \)
  - \( x/b = 0.25 \)
  - \( x/b = 0.4 \)

The plots show the relationship between \( z/h \) and \( \langle u \rangle / U_s \) for different \( x/b \) values, indicating the max gradient at each point.
The flow on the leeward side is going up and the flow on the windward side is going down forming a primary recirculation.
TKE

Max TKE
Skewness of W
Kurtosis of U

Extreme values of streamwise velocity occur frequently at roof-level.
Kurtosis of w

\[ x/b = -0.4 \quad x/b = -0.25 \quad x/b = 0.0 \quad x/b = 0.25 \quad x/b = 0.4 \]
RESULTS & DISCUSSIONS

Mathematic equations
NUMERIC METHOD

- Time derivative
  - Implicit second-order accurate backward differencing

- Spatial derivative (gradient, divergence, and laplacian terms)
  - Second-order accurate Gaussian finite volume integration scheme

- Interpolation scheme (cell surfaces’ value)
  - Central differencing using values from cell center
MATHEMATICAL EQUATIONS

- Mass conservation equation:
  \[ \frac{\partial \bar{u}_i}{\partial x_i} = 0 \]

- Momentum conservation equation:
  \[ \frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j} \bar{u}_i \bar{u}_j = -\Delta P \delta_{i,1} - \frac{1}{\rho} \frac{\partial \bar{\pi}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_i \partial x_j} \]

- Resolved scale modified pressure
  \[ \bar{\pi} = \bar{p} + \frac{2}{3} k_{SGS} \]
MATHEMATICAL EQUATIONS

- The SGS Reynolds stresses (Smagorinsky, 1963)

\[-\tau_{ij} = -(\bar{u}_i u_j - \bar{u}_i \bar{u}_j) = v_{SGS} \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_i}{\partial x_i} \right) + \frac{2}{3} k_{SGS} \delta_{ij} \]

- SGS turbulence viscosity

\[v_{SGS} = C_k k_{SGS}^{1/2} \Delta \]

- Filter width

\[\Delta = [\Delta_1 \Delta_2 \Delta_3]^{1/3} \]

- Modeling constant

\[C_k = 0.07 \]
MATHEMATICAL EQUATIONS

- One-equation SGS model (Schumann, 1975)

\[
\frac{\partial k_{SGS}}{\partial t} + \frac{\partial}{\partial x_j} \bar{u}_i k_{SGS} = -\frac{1}{2} \tau_{ij} \frac{\partial \bar{u}_i}{\partial x_j} + (\nu + \nu_{SGS}) \frac{\partial^2 k_{SGS}}{\partial x_i \partial x_j} - C_\varepsilon \frac{k_{SGS}}{\Delta}
\]

- modeling constant \( C_\varepsilon = 1.05 \)
MATHEMATICAL EQUATIONS

- Scalar transport equation

\[ \frac{\partial \phi}{\partial t} + \frac{\partial}{\partial x_j} \bar{u}_i \phi = \frac{\partial \gamma_i}{\partial x_i} + \frac{\nu}{Sc} \frac{\partial^2 \phi}{\partial x_i \partial x_j} \]

- Schmidt number

\[ Sc = 0.72 \]

- SGS pollutant flux

\[ \gamma_i = \phi \bar{u}_i - \phi \bar{u}_i = -\frac{\nu_{SGS}}{Sc} \frac{\partial \phi}{\partial x_i} \]