Thermal stratification and vegetation effects on the urban micro-climate – a CFD study

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Motivation:

- Singapore - a very heterogeneous urban morphology.
- Increasing population and UHI phenomenon => land and liveability challenge.
- Need for better urban planning and designing that provides good thermal and aural comfort.

Aim:

- Improve our understanding on urban-microclimate – CFD and measurements.
- Develop an Urban Microclimate-Multi physics Integrated Simulation Tool (UM-MIST) that incorporates effects of thermal stratification, vegetation, anthropogenic heat flux and waterbody.
Objective:

CFD on a residential estate in Singapore.
(i) Neutral flow
(ii) Unstable stratified flow
(iii) Unstable stratified flow and vegetation.
Computational Domain of a Residential Estate

- Terrain – approx. 5 m above ground.
- Building height - 10 m to 60 m.
- Assumption - smooth wall.
- Seletar met - \( u = 4 \text{ m/s} \) @ \( z = 14 \text{ m} \)

North & East – logarithmic profile
- South & West - outflow
- Top – symmetry
- Bottom – very rough wall outside RE
Numerical settings:

- Snappy Hex methodology.
- Six levels of mesh refinement (min. res. = 0.3125 m at the building corner and max. res. = 20 m).
- $k_s$ and $c_s$ are chosen such that they satisfy the near-wall mesh criteria (Blocken et al. 2007).
- Total no. of cells = 8.5 million.

- StarCCM+ v 9.06 (SC+) and OpenFOAM v 2.3 (OF) – same mesh.
- Steady RANS + $k-\varepsilon$ turbulence closure.
- Thermal effects with Boussinesq approximation.
- Second-order schemes for Navier-Stokes.
- Turbulence - First-order in OF and Second-order in SC+.
- SIMPLE pressure-velocity coupling
Neutral flow
Approach flow

- $U_{ref}$ and $k_{ref}$ are at $h = 60$ m at inflow
- Small increase in $k$ with increasing distance from inlet
- Larger peak in $k$ near the ground for SC+
Contours of velocity magnitude @ z = 10 m

StarCCM+  
OpenFoam

Good qualitative agreement
Vertical profiles from SC+ and OF:

- For $z \leq h$, SC+ shows slightly larger values of $u$ and $k$ than OF
- A fair quantitative agreement for neutral flow
Unstable flow
A 2-D validation study for buoyancy (Allegrini et al., 2014):

- **Inlet** – measured values of $u$ and $k$.
- **Outlet** – convective boundary condition
- **Top** – symmetry
- **Bottom** – smooth wall
- **Canyon surfaces** – uniformly heated to 70°C
- $Re = 19200$ and $Fr = 6.75$
- $0.05 < y^+ < 4.5$; 30800 cells.

Source: Fig. 1 in Allegrini et al., 2014
Comparison of SC+ and OF with experiments:

- For $T$, SC+ performs well close to the bottom canyon.

- Overall, a good agreement between SC+ and OF with experiments.
Temperature contour @ z = 10 m - OpenFoam

All surfaces uniformly heated to 35°C, 5°C higher than the inlet.
Contours of $T @ z = 10m$

OF shows lower values of $T$ than SC+ - why?
Neutral and unstable profiles are almost same in OF => weak buoyancy.
Could it be due to better wall treatments in SC+ ? – a 3D validation study
Further slides: starccm+
CFD coupling with solar irradiance
Modelling of Solar irradiance – surface heat flux input to CFD:

- Perez all-weather sky model for natural light source from the sun and the sky dome.
  - Proven to be good for Singapore
  - Input – direct normal irradiance and diffuse horizontal irradiance for a given date, time and geographical location.
  - Output – direction and radiation intensity of light sources.

- Ray tracing solver to account for ambient bounces.
  - Lambertian model for surface diffusivity
  - Ambient bounces = 2
  - Appropriate absorption coefficient for different types of surfaces (waterbody, concrete, pavement, grass, glass, wall)

- Radiance solver; simulations at 16:30 p.m. on June 21.
Temperature contours at z = 10 m:

Uniform surface temperature

Coupling with solar irradiance (non-uniform surface heat flux)
Temperature contours at $z = 10\, \text{m}$:

- Uniform surface temperature
- Coupling with solar irradiance (non-uniform surface heat flux)

A very different distribution of temperature!!!!
Vertical profiles of unstable flow:

Notable differences in the vertical profiles of $k$ and $T$
Modelling vegetation
A validation study (Gromke & Blocken, 2015):

- **Domain size** – $40h \times 24h \times 8h$ & 0.8 million mesh points.
- **Inlet** – power law.
- **Outlet** – pressure outlet.
- **Top & Span** – symmetry
- **Bottom** – rough wall except the buildings and street canyon.
- **Vegetation** – pressure loss coeff = $250 /m$; 97% pore volume fraction
Comparison of SC+ and OF with experiments:

No trees in street canyon

Trees in street canyon

Improvement in OF tree modelling is required
Vegetation in a residential site:

- Additional source terms in the transport equations.
- Tree specs:
  - Crown – 5 m x 5 m x 6 m
  - Trunk – 6 m tall
  - Distance = 10 m
  - LAD = 0.55 m²/m³
  - Cooling power = 137.5 W/m³.
- Shading of trees is ignored.

(Gromke et al., 2015)
Vegetation in a residential site:

Avenue 1

Avenue 2
Temperature and TKE profiles along Avenues at z = 7m:

- Max. temperature reduction in presence of trees is \( \sim 2^\circ C \)
- Is it due to lower turbulent kinetic energy? May be or may not be!
### Summary:

<table>
<thead>
<tr>
<th>Type of flow</th>
<th>Vegetation</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral</td>
<td>-</td>
<td>Good agreement between SC+ and OF</td>
</tr>
<tr>
<td>Unstable (constant T)</td>
<td>-</td>
<td>Weaker buoyancy in OF</td>
</tr>
<tr>
<td>Unstable (non-uniform heat flux)</td>
<td>-</td>
<td>Notable difference in flow and temperature distribution</td>
</tr>
<tr>
<td>Unstable (non-uniform heat flux)</td>
<td>yes</td>
<td>Temperature reduction of 2°C.</td>
</tr>
</tbody>
</table>
Further work:

- Improve OF modelling for temperature/heat flux and vegetation.
- Incorporate features viz. shading of trees, anthropogenic heat flux
- Extend the computations to a district size and compare with field measurements.
Acknowledgements
THANKYOU