Wind tunnel investigation of the spatial variability of turbulence characteristics in the urban area of Basel City, Switzerland

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Agenda

• Motivation and overview BUBBLE project
• Remarks on general modelling approach
• Approach flow
• Urban flow
• Summary and Outlook
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The BUBBLE project investigates turbulence and dispersion phenomena in the Urban Boundary Layer (UBL) of Basel, CH.

Major activities
- Operation of an extensive net of field measurement stations
- Simulation of dispersion scenarios with numerical models
- **Realization of a wind tunnel study to model turbulence and dispersion scenarios**

Timeline
- **2001/02**: Yearlong operation of measurement stations in Basel
- **2003**: Wind tunnel study on turbulence in the UBL of Basel
- **2004**: Wind tunnel study on pollutant dispersion in Basel

Participating institutions (e.g.)
- ETH Zürich, University of Basel, University of Hamburg (MI)
- Many, many more (see project website)

Further information [http://www.unibas.ch/geo/mcr/Projects/BUBBLE/](http://www.unibas.ch/geo/mcr/Projects/BUBBLE/)
The wind tunnel study contributes systematic and extensive turbulence and dispersion measurements over the urban roughness of Basel, CH.

Motivation

- Complement the field measurements
- Support the interpretation of the field measurements in Basel (e.g. temporal and spatial representativeness)
- Provide reference and validation data for numerical modelling

Provide detailed and well-documented turbulence and dispersion data

Study dispersion phenomena under systematically varying boundary conditions

- Provide reference and validation data for numerical modelling
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The wind tunnel study is conducted in the Large Boundary Layer Wind Tunnel, 'WOTAN', at the Meteorological Institute of the University of Hamburg.
The specification of the urban area is given by an extensive CAD model provided by the authorities of Basel, CH.

Model scale: 1:300
Model area: ~ 2.4km x 1.2km
No. of houses: ~ 3.200
Instantaneous velocity measurements are conducted with two dimensional laser Doppler anemometry (LDA).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simultaneously measured velocity components</td>
<td>2 velocity components</td>
</tr>
<tr>
<td>Measurement accuracy</td>
<td>~0.05m/s</td>
</tr>
<tr>
<td>Measurement volume (ellipsoid)</td>
<td>~1.5mm x 0.12mm x 0.12mm</td>
</tr>
<tr>
<td>Measurement frequency</td>
<td>up to $10^3$ Hz</td>
</tr>
<tr>
<td>Automatic probe positioning accuracy</td>
<td>~1mm</td>
</tr>
</tbody>
</table>
Focus of the modelling approach is on the flow within the urban surface layer (~150m above ground) under neutral stratification.
Basic similarity laws and transfer functions are applied to ensure applicability of wind tunnel results to the full scale scenario.

### Similarity number

<table>
<thead>
<tr>
<th>Reynolds number</th>
<th>Criterion</th>
<th>Realization</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Re independency above $\text{Re}_{\text{crit}}$ (VDI*)</td>
<td>$\text{Re}<em>{\text{mod}} = \frac{-u</em>{\text{ref}} \cdot L_{\text{ref}}}{v} &gt; \text{Re}_{\text{crit}} \approx 10,000$</td>
<td>$\text{Re}_{\text{mod}} \approx 10^1 \cdot 10^{-1} \approx 60,000$</td>
</tr>
<tr>
<td>Roughness Reynolds number 1 Ensuring insignificance of viscous effects (VDI*)</td>
<td>$\text{Re}<em>* = \frac{u</em>* \cdot z_0}{v} &gt; 5$</td>
<td>$\text{Re}_{\text{approach flow}} \geq 15$</td>
</tr>
</tbody>
</table>

### Parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Transfer function</th>
<th>Application (e.g.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length scales</td>
<td>$L_{\text{mod}} = \frac{L_{\text{full scale}}}{300}$</td>
<td>$z_0, d_0, L_{ux}, L_{wy}, L_{uz}$</td>
</tr>
<tr>
<td>Time scales</td>
<td>$T_{\text{mod}} = \frac{T_{\text{full scale}}}{300}$</td>
<td>Spectra $S_\nu$ in frequency space</td>
</tr>
</tbody>
</table>

*VDI guideline 3783 from December 2000
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The approach flow is modelled according to measured profiles and references appropriate for Basel, CH.

**Roughness classification of approach flow:**
- „moderately rough“ / „rough“ (VDI)
- Roughness class 5 (Davenport)

**Target values for modelling (mean wind profile):**
- Profile exponent: \( \alpha \approx 0.18 \)
- Roughness length: \( z_0 \approx 0.2m \)
The modelled mean wind and turbulence intensity profiles of the approach flow correspond well to references.

<table>
<thead>
<tr>
<th>Mean wind profile</th>
<th>Turbulence intensities (e.g.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(dotted line: height of roughness elements)</td>
<td>(references from VDI guidelines)</td>
</tr>
</tbody>
</table>

\[ \begin{align*}
\alpha &= 0.19 \\
\zeta_0 &= 0.19 m \\
\eta_0 &= 0 m \\
u_+ / u(156m) &= 5.8% \\
\end{align*} \]
A „constant flux“ layer is well-established and the turbulence spectra coincide with references.

| Reynolds stress $u'w'$ | Spectral densities (e.g.)
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(reference: Kaimal (1972))</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$z$ [m]</th>
<th>$f \cdot S_{uu}/u_*^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>50</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>100</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>150</td>
<td>$10^{0}$</td>
</tr>
<tr>
<td>200</td>
<td>$10^{1}$</td>
</tr>
</tbody>
</table>

$n = fz/u$
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The urban flow study focuses on three aspects.

<table>
<thead>
<tr>
<th>Study objective</th>
<th>Study approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow development</td>
<td>Analysis of vertical profiles along the model axis</td>
</tr>
<tr>
<td>Horizontal inhomogeneity</td>
<td>Analysis of horizontal mesh profiles at 5 height levels in and above the RS</td>
</tr>
<tr>
<td>Variability of vertical profiles</td>
<td>Analysis of 9 vertical profiles in the vicinity of BSPR (above roof level)</td>
</tr>
</tbody>
</table>
The flow over the core model area is still developing.
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The flow over the core model area is still developing.
Two vertical profiles from street level upward give further indication of a still developing flow over the core model area.

<table>
<thead>
<tr>
<th>Mean wind speed $u$</th>
<th>Turbulence intensity $I_u$</th>
<th>Reynolds stress $u'w'$</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Graph 1" /></td>
<td><img src="image2.png" alt="Graph 2" /></td>
<td><img src="image3.png" alt="Graph 3" /></td>
</tr>
</tbody>
</table>

Street I at $x = 1.5$ km

Street II at $x = 1.8$ km
Horizontal turbulence measurements allow an assessment of the horizontal flow inhomogeneity within the RS.

173 measurement points per layer:
The turbulence intensity $I_u$ (e.g.) was measured at five height levels.
The turbulence is horizontally inhomogeneous up approximately $3z_H$. 

\[ z \approx 1.8z_H \]
The turbulence is horizontally inhomogeneous up approximately $3z_H$.

\[ z \approx 2.3z_H \]

(0,0): measurement tower BSPR
The turbulence is horizontally inhomogeneous up approximately $3z_H$. 

$z \approx 2.7z_H$
The turbulence is horizontally inhomogeneous up approximately $3z_H$. 

\[ z \approx 3.1z_H \]
The turbulence is horizontally inhomogeneous up approximately \( 3z_H \).

\[
\frac{z}{z_H} \approx 4.7
\]

\( z = 4.7z_H \)

\( (0,0): \) measurement tower BSPR
Vertical profiles in the RS depend significantly on the measurement location.
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The preliminary data analysis already allows first conclusions.

<table>
<thead>
<tr>
<th>Observation</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>At x = 1.2km to 1.6 km:</strong> Horizontal flow homogeneity increases significantly above $z \approx 3z_H$.</td>
<td>$z \approx 3z_H$ appears to be a reasonable height estimation for the urban roughness sublayer in Basel, CH.</td>
</tr>
<tr>
<td><strong>At x = 1.5km and x = 1.8km:</strong> A „constant shear“ layer is well-established between $z \approx 50$m and $z \approx 100$m with decreasing „constant shear“ from $x = 1.5$km to $x = 1.8$km.</td>
<td>An inertial sublayer up to $z \approx 100$m with approx. constant shear stress and logarithmic wind profile* can exist even over urban roughness.</td>
</tr>
</tbody>
</table>

*not shown in this presentation
Outlook

Quantitative analysis of turbulence data

- Application of appropriate scalings to the profiles
- Computation of horizontally averaged mean profiles in the RS with corresponding scatter widths
- Comparison to full scale data from Basel

Dispersion experiment (2004)

- Modelling the tracer release experiment in Basel
- Systematic measurement of concentration data for numerical model evaluation