Developments in modelling building wake effects on dispersion in ADMS

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Real world building effects


Photograph by Martin Tasker
Building module formulation
Buildings influenced flow & dispersion

• ADMS & AERMOD include:
  – Near wake (cavity)
  – Main wake (descending streamlines)
  – Two plume approach
Building module formulation
Using ADMS and AERMOD to model building effects

ADMS

IDEALISE COMPLEX
AS A SINGLE BLOCK

AERMOD (PRIME)

BPIP combines buildings using the ‘a’ lines and only those ‘b’ lines that are less than L. All ‘a’ lines are assumed to be less than L. The outside portion of the lines used form the perimeter of the Gap-Filling Structure (GFS).

L = min (building height, projected building width)
Building module formulation
Using ADMS and AERMOD to model building effects

Evaluate flow field

Calculate entrainment

Calculate concentrations

Source Q

Uniform concentrations

Two-plume concentration distribution

Recirculating flow region

Turbulent wake

Entrainment

$(1-\varepsilon)Q$

$\varepsilon Q$
## Building module formulation

### Using ADMS and AERMOD to model building effects

<table>
<thead>
<tr>
<th>Item</th>
<th>Comparison</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean flow in main wake</td>
<td>Different</td>
<td>ADMS uses wake deficit model; AERMOD uses a fractional deficit of 0.7 modified by the location within the wake.</td>
</tr>
<tr>
<td>Turbulence</td>
<td>Different</td>
<td>ADMS assumes velocity variances increase in proportion to the wake-averaged surface shear stress; AERMOD derives the turbulent velocity from empirical expressions and ambient values.</td>
</tr>
<tr>
<td>Effective building</td>
<td>Different</td>
<td>ADMS applies an algorithm that assesses each building in the vicinity of the ‘main’ building in terms of its relative height and crosswind separation; AERMOD combines buildings if they are separated by less than a characteristic dimension of each building (larger of height and projected width).</td>
</tr>
<tr>
<td>Cavity length and height</td>
<td>Similar</td>
<td>n/a</td>
</tr>
<tr>
<td>Wake height/width</td>
<td>Different</td>
<td>AERMOD depends solely on effective building properties; the ADMS formulation also includes a dependence on $u^*/U_{14}$.</td>
</tr>
<tr>
<td>Streamline defln</td>
<td>Different</td>
<td>Similar concepts but different expressions used.</td>
</tr>
<tr>
<td>Plume spread</td>
<td>Different</td>
<td>ADMS: calculates wake-affected spread parameters from non-building parameters accounting for differences in flow &amp; turbulence; AERMOD models a p.d.f. growth (near wake) transitioning to eddy diffusivity growth (far wake).</td>
</tr>
<tr>
<td>Cavity concentration</td>
<td>Different</td>
<td>Both models determine a fraction entrained into the cavity, but the expressions used for the amount entrained and for the resulting cavity concentrations differ.</td>
</tr>
<tr>
<td>Wake concentration</td>
<td>Different</td>
<td>Both models have sum a non-entrained part of the original plume and a ground based plume from the cavity region; the formulations of those expressions differ.</td>
</tr>
</tbody>
</table>
• Divided into regions:
  – R – recirculating flow (near wake)
  – W – wake
  – U – directly upwind
  – A – remainder of perturbed flow around building
  – E – region external to the wake

• W and E form the main wake
Building module formulation

ADMS wake modelling – near wake

\[ L_R = \frac{AW_B}{1 + BW_B/H_B} \]

\[ A = 1.8 \left( \frac{L_B}{H_B} \right)^{-0.3}, B = 0.24 \]

\[ L_B \geq \min(H_B, 0.5W_B) \quad \text{– roof flow reattaches} \]

\[ L_B < \min(H_B, 0.5W_B) \quad \text{– roof flow separates} \]
Building module formulation
ADMS wake modelling – main wake

- Flow field:
  \[ u = U_H \left\{ 1 - \hat{u} \left[ \frac{W_B}{2\lambda_y} \right] \left[ \frac{H_B}{\lambda_z} \right]^2 g(\xi)h(\eta) \right\} \]
  
  - similarly for \( v \) and \( w \)

- Wake averaging:
  \[ \frac{\Delta u}{U_H} = \frac{1}{2} \hat{u} \left( \frac{W_B}{2L_y} \right) \left( \frac{H_B}{L_z} \right) \left( \frac{H_B}{\lambda_z} \right) \Delta \tau = U_H \Delta u \left( \frac{L_z}{x-x_0} \right) \]
  \[ \Delta \sigma_v^2 / \sigma_v^2 = \Delta \sigma_w^2 / \sigma_w^2 = \Delta \tau / u_s^2 \]

- Wake spread parameters:
  \[ \frac{d\sigma_{yw}}{dx} = \left( \frac{\sigma_{yw}}{2} \right) \frac{d(\Delta u/U_H)}{dx} + \left[ \left\{ 1 + \left( \frac{\Delta \sigma_v^2}{\sigma_v^2} \right)^{1/2} \right\} f \left( 1 - \frac{\Delta u}{U_H} \right) \right] \frac{d\sigma_{yE}}{dx} \]
  
  - similarly for \( w \)
Building module formulation
ADMS model developments

• Improvements to the transition between building effects regions:
  – smooth the concentration in the transition from the near wake to the main wake
  – Ensure plume spread continuity for a rising/falling plume crossing between the Wake and External regions

• Adjustments for wide buildings when the flow may be close to 2-dimensional
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ADMS model validation
Thompson

• Wind tunnel study
• Varying stack heights & locations
• 4 different buildings:
  – a cube
  – a wide building (2 cubes aligned crosswind)
  – a wider building (4 cubes aligned crosswind,
    – a long building (2 cubes aligned along wind)
• Sources and receptors aligned with the building centreline
• Receptors at ground level
• ‘Building’ and ‘no building’ scenarios
• Neutral meteorology (free stream wind ~ 4 m/s)

ADMS model validation
Thompson – Wind Profile

- 2 minute average for the results in Thompson study; concentrations reproducible within 5%.

- ADMS uses measured vertical profiles of wind speed and turbulence
  - Wind speed: \( u(z) = 2.2\left(\frac{z}{10}\right)^{0.136} \)
  - Measured turbulence profiles show some decay along wind tunnel
ADMS model validation
Thompson – Observed and modelled data – No building
ADMS model validation
Thompson Cubic building. Observed - Max building/Max no building
ADMS model validation
Thompson – Observed Data. 32m stack, cubic building

CERC
ADMS model validation
Thompson – Modelled Data. 32m stack, cubic building
ADMS model validation
Thompson – Comparison. 32m stack, cubic building
ADMS model validation
Thompson – Observed Data. 92m stack, cubic building
ADMS model validation
Thompson – Modelled Data. 92m stack, cubic building
ADMS model validation
Thompson – Comparison. 92m stack, cubic building
ADMS model validation
Thompson Cubic Building. Ratio Max Modelled/Max Observed

Distance from Upwind Face of the Building (m)

Stack Height (m)

-720 -600 -480 -360 -240 -120 0 120 240 360 480 600 720

0 30 60 90 120 150 180 210

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ADMS model validation
Thompson Long Building. Ratio Max Modelled/Max Observed

Distance from Upwind Face of the Building (m)
Stack Height (m)

-720 -600 -480 -360 -240 -120 0 120 240 360 480 600 720
0 30 60 90 120 150 180 210

Colors indicate the ratio:
- Red: ≥2.00
- Orange: 1.75
- Yellow: 1.50
- Green: 1.30
- Light green: 1.15
- Light blue: 1.00
- Blue: 0.85
- Cyan: 0.75
- Light purple: 0.65
- Purple: 0.55
- Light blue: ≤0.5
ADMS model validation
Thompson Wide Building. Ratio Max Modelled/Max Observed
ADMS model validation

Thompson Wider Building. Ratio Max Modelled/Max Observed
ADMS model validation
Thompson Wider building. Observed - Max building/Max no building
ADMS model validation
Thompson – Comparison. 92m stack, wider building
Oil well pad on the North Slope of Alaska
- Modelled emissions from one drilling rig over 40 days
- Three main sources modelled
- One monitor, very close to sources
- Measured NO$_x$, NO$_2$ & O$_3$ concentrations
- Measured met conditions:
  - wind speed (horizontal & vertical) & direction
  - standard deviation of wind direction
  - temperature
  - total radiation
  - standard deviation of the vertical wind speed

Acknowledgements: BP International Limited funded the Prudhoe Bay ADMS validation study.
At Prudhoe Bay, met and concentration measurements were co-located, approximately 60 m from the rig.

- Look at how the standard deviation of the vertical wind speed, $\sigma_w$, varies with wind direction.
- The monitor is recording the increase in vertical turbulence generated by the rig structure.

Clear peak in $\sigma_w$ when the wind blows from the rig to the monitor (~117°)
The ADMS predictions of $\sigma_w$ are good when the model predicts the receptor to be in the ‘building effects region’...

...but the ‘building effects region’ does not extend far enough laterally in these very stable conditions.
ADMS model validation
Prudhoe Bay

Building-influenced flow regions for the Prudhoe Bay study

Region A - ADMS models building-induced turbulence for the majority of wind directions
Region B - The measurements show a significant increase in turbulence, not modelled by ADMS
Region C - The turbulence decays away from an elevated value due to the presence of the buildings down to ambient values, not modelled by ADMS
Region D - Ambient values of turbulence

Ratio of observed $\sigma_w$ to modelled non-buildings $\sigma_w$
Conclusions & further work

- For the Thompson experiment measurement-model comparisons are generally good except for high upwind sources and for some sources near buildings
  - Modification to vertical mixing for plume above main wake
  - Modification to vertical velocity above near wake (recirculation)

- The Prudhoe Bay field observations show that the transverse extent of enhanced turbulence is underestimated
  - Include generation of turbulence by buildings other than effective building