H14-303

SIMPLE BUILDING DOWNWASH FORMULAS FOR GROUND-LEVEL CONCENTRATIONS AND PLUME RISE

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Abstract

Context: In Flanders, several heavy metal industries face difficulties in meeting the upcoming air quality standards for Pb, Ni, As and Cd due to building downwash causing high pollutant concentrations within a few building heights. Current models perform poorly at this very short distance (Olesen et al., 2009). Therefore, we started the development of a new building downwash model.

Concept and construction of the model: The model is simplified to a single building down-washed plume (BDW-plume) with additional in-mixing of air at short distances of the stack. For a given stack-building configuration, we determine for which height a plume from an isolated stack produces the same maximum ground-level concentration Cmax as measured under the BDW-plume. The origin of the x-axis is at the foot of the stack. The position of the ground-level concentration maximum is xi_max for the isolated stack and xb_max for the BDW-isolated stack produces the same maximum ground-level concentration Cmax as measured under the BDW-plume.

Computational aspects of model use: Given a particular plume-building-receptor configuration, one computes xb* = xb + Δ(xb). This xb* is to be used for the distance x in the dispersion parameters σz(x) and σ(x) when calculating the ground-level concentration. In the Briggs plume rise equations, only that part of the plume rise between 2 xb and xb* must be considered, and x must be decreased by 2 xb*.

Verification ground-level concentrations: The maxima concentrations of the 330 Thompson profiles are reproduced with a R²=0.95 and a regression equation: y = 1.009 x. Eighty percent of the individual profiles are reproduced with a correlation greater than 0.88.

Application: This model has been used for several heavy metal plants in Belgium to identify the (small) sources that are causing current exceedance of future air quality standards, and to compute stack heights and/or emission reductions required for the future air quality standards.

INTRODUCTION

We present a model based on the Gaussian transport and diffusion equation that is able to reproduce the more than 300 ground-level concentrations profiles (GLCPs) measured by Thompson (1991,1993). This dataset, and some of our earlier work on it, is presented in Cosemans and Lefebvre (2010).

In the next paragraph, the effect of building downwash is demonstrated. Thereafter, a new theory for describing the ground level concentrations is given. An example is provided in the following paragraph in order to demonstrate the methodology. After discussing the determination of the parameters, some results are shown, both for the concentration levels and for the parameter values. Finally, some considerations about plume rise are given and conclusions are presented.

STACK POSITION RELATIVE TO THE BUILDING

The ground-level concentration profile measured for an emission through a stack varies with the position of that stack relative to a building. Fig. 1 is based on Thompson’s measurements for a cubic building, where the stack height Hs is equal to the building height Hb. If the stack is located on the roof of the building, the peak ground-level concentrations occur very close to the stack. When the stack is moved away of the building, the peak concentration decreases and is found at a larger distance from the stack. Fig. 2 shows the peak values (it is, the maximum concentration found in each respective concentration profile, corresponding to one specific set of building height, building width, building length, location of stack and height of stack) of the GLCPs for the same building as in Fig. 1 versus the position of the stack relative to the building. As one can see, an enormous effect of building downwash is found, and the peak concentration is strongly dependent on the location of the stack. Fig. 3 shows the peak concentrations versus stack-building position for the other stack heights used by Thompson, heights that ranged from 0.5 Hb till 2.5 Hb.

The new model is based on the idea that the GLCPs measured by Thompson can be reproduced by the bi-Gaussian diffusion and transport equation, where (1): the geometric distances between source and receptors are increased with ‘virtual distances’ that are related to the extra in mixing of air due to the increased turbulence near the building, and (2): that these ‘virtual distances’ are a function of the stack-building geometry. Point (1) is worked out in section ‘the virtual plume’, point (2) in the section ‘curve fitting’.

Topic 6: Inverse Dispersion Modelling and Source Identification
Before Displacement, Before parameter calculation and the geometric distance $x$ between the foot of the stack and the receptor is defined by three functions $\sigma_x(x), \sigma_y(y)$ and $x^*$ are the horizontal and vertical dispersion parameters. Cosemans and Lefebvre (2010) derived following expressions for the wind tunnel:

- $\sigma_x(x) = (0.382 + 0.0001(4.5H - 150))x^{0.711}$ (3)
- $\sigma_y(y) = (0.418 - 0.0001(4.5H + 500))y^{0.796}$ (4)

- $H^*$ and $x^*$ refer to a receptor dependent virtual plume origin.

It should be noted that equation (1) can be interpreted as defining a ‘virtual’ Gaussian plume, that produces the same ground-level concentration profile as the building down-washed plume. It does not reproduce the vertical concentration distribution, as discussed later.

$x^*$ refers to the horizontal component of the virtual origin. The difference between the distance $x^*$ to be used in the dispersion parameter calculation and the geometric distance $x$ between the foot of the stack and the receptor is defined by three functions which we call Displacement, Before and After. Displacement is a constant, usually representing an upwind displacement, Before and After are functions of $x^*$; they are a measure of the increased in-mixing of air into the plume near the source. For a receptor at a distance $x$ from the stack, $x^*$ is computed as following:

$$x^* = \frac{H_x}{H}$$

where $H_x$ is the distance from the stack to the building for the cubic building, $H_x=H_b$.
\[ x_0 = x + \text{Displacement} \]  
\[ x_f = x_0 + \text{Before}(x_0) \]  
\[ x* = x_f + \text{After}(x_f) \]  
(5.1)  
(5.2)  
(5.3)

Before and After refer to \( X_{C_{\text{max}}} \), the location of the maximum ground-level concentration, given by:

\[ X_{C_{\text{max}}} = 17.65 \times (H_{\text{final}}) \]  
(6)

where \( H_{\text{final}} \) is the final height of the virtual plume. Before \( (x_0) \) increases linearly from 0 to \( B_f \) over the interval between \( x_0 \) and \( X_{C_{\text{max}}} \). After \( (x_f) \) increases from 0 to \( A_f \) over the interval between 0.9 \( X_{C_{\text{max}}} \) and \( \min(6 \times H_b, 2A_f) \), where \( H_b \) is the building height.

The vertical component of the virtual origin \( H^* \) is equal to the stack height \( H \) at \( x^*=0 \) and decreases linearly to \( H_{\text{final}} \) at \( X_{C_{\text{max}}} \).

**HOW IT WORKS: AN EXAMPLE**

Fig. 4 illustrates how these definitions produce a GLC-profile for the case \( X_s=300 \) mm, \( H_s=H_b=150 \) mm. The parameter values used are \( H_{\text{final}}=45 \) mm, \( \text{Before}=434 \) mm, \( \text{After}=175 \) mm and \( \text{Displacement}=-428 \) mm.

**CURVE FITTING OF PARAMETERS**

Equation (1) can be evaluated for each of the measured GLC-profiles provided we know the values of \( H_{\text{final}}, \text{Displacement}, B_f \) and \( A_f \) for each building-stack configuration. Optimal values for these parameters have been determined and functions have been fitted through these values so that, for a given building type, the values of \( H_{\text{final}}, \text{Displacement}, B_f \) and \( A_f \) are given by an expression of the form:

\[ (A_1G_{1,H_s} + B_1G_{2,H_s} + C_1)(G_{3,X_s}) + (A_2G_{4,H_s} + B_2G_{5,H_s} + C_2)(G_{6,X_s}) \]  
(7)

where \( A_i, B_i \) and \( C_i \) are constants and \( G_{i,H_s/X_s} \) is a Gaussian function with mean \( \mu_i \) and spread \( \sigma_i \). \( \mu_i \) and \( \sigma_i \) can be functions of \( H_s \) and/or \( X_s \).
SOME RESULTS

Fig. 5 shows that the GLC’s computed with the fitted parameters compare well with GLC-profiles from some duplicated measurements. Fig. 6 shows that the peak values of the observed GLC-profiles are well reproduced by this model, with \( R^2 = 0.958 \). For 88.8% of GLC-profiles, the observed peak concentration is within 33% of the predicted one.

Fig. 7 shows all peak values for the cubic building; this figure is equal to Fig.3, except that the peak concentrations of the reproduced GLC-concentrations are added as obtained after curve-fitting of the optimal values. (Using the optimal values, the reproduction would be almost identical to the measurements – in part due to noise fitting.)

Fig. 9 shows the smoothed values of the parameters \( H_{\text{final}} \) (shown: \( \Delta h = H_{\text{final}} - H_s \)), Displacement, Before and After for each of the four building types used by Thompson.

VALUES OF THE PARAMETERS

Fig. 9 shows the smoothed values of the parameters \( H_{\text{final}} \) (shown: \( \Delta h = H_{\text{final}} - H_s \)), Displacement, Before and After. The graphs are constructed in a way similar to Fig.3, except that it shows the parameter values not only for the cubic building, but for all building types discussed by Thompson (1993). The thin blue horizontal line segments refer to the stack height \( H_s \), the curved...
segments on the same x-interval give the parameter value when the stack is moved from upwind (usually -12 Hb) to downwind position (till 12 Hb) of the building. Due to the components of the curves used for curve fitting (Eq.7), these curve segments are basically the sum of two Gaussian clock-curves. Some observations:

- The ‘deepest’ value of $\Delta h$ is roughly 150 mm (that is: building height), except when the stack is low; it is 50 mm for $H_s$=75 mm and 100 mm for $H_s$=150 mm. The deepest value occurs downwind of the building for low stacks at 2 to 4 times Hb; for higher stacks, the largest decrease is for stacks above the building. For the very wide building, $\Delta h$ remains significant even for stacks of 450 mm.
- Before follows a simple Gaussian clock-curve for the long building. When the building gets wider, Before shows a local minimum at Xs = 3 Hb. Before is always largest for stacks with height equal to the height of the building.
- After has the largest values for stacks that are lower than the building. After increases with the width of the building, but is quite independent of stack height is this is above building height.
- Displacement is usually upwind, although for the long building, plumes from high stacks have a displacement value greater than zero, because their greatest GLC is found at a (slightly) greater distance than is the case for the plume from an isolated stack. Extreme values of (upwind) displacement range from 3 Hb (long building) till 5 Hb (wide building). These extreme values occur at Xs = 2 Hb.

The curves on Fig.9 show that the impact of a building on the GLC-profile of a plume is a continuous function that affects plumes from stacks located in an upwind/downwind interval of about ± 15 Hb long.

VERTICAL CONCENTRATION PROFILE AND PLUME RISE

Thompson did not measure vertical concentration profiles, but Hubert et al. (1980) did so in the same wind tunnel (with a smoother floor). These measurements show clearly that the maximum in the vertical profile is located at stack height. The rough sketch in Fig.8 illustrates the difference between the real vertical profile and the vertical profile one obtains if Eq.1 was extended to give a vertical profile. This means there is more in-mixing of ambient air in the plume than is suggested by the parameters $H_{final}$, Displacement, Before and After.

The Briggs plume rise equation has a gradual plume rise that stops after a certain distance $x_{final}$ where atmospheric turbulence begins to dominate entrainment. For the field we use:

$$\Delta h_{Thermal\_Building\_Downwash}(x) = \Delta h_{Briggs}(x) - \Delta h_{Briggs}(2(x^* - x)) \quad (8)$$

The $\Delta h$ component of $H^*$ is found to be wind speed dependent. Including Eq. 8, $\Delta h_{field}$ is currently:

$$\Delta h_{field} = \max(-H_{Stack}, \Delta h_{wind\_tunnel} \cdot (u/2.2)^2 + \Delta h_{Thermal\_Building\_Downwash}(x)) \quad (9)$$

CONCLUSIONS

We presented a model that is able to reproduce the 339 ground-level concentration profiles measured by Thompson. The model performs well on this data set. We applied the model to some Belgian industrial sites that are assumed to have building downwash causing pollutant high concentrations at very short distances from the sites. The model predicts concentrations close to measurements using the additional Eqs. 8 and 9, which take into account plume rise and wind speed affecting the degree of building downwash.

REFERENCES


Hubert, A.H. et al., 1980: The effects of a squat building on short stack effluents, US EPA 600/4-80-055

