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 x_{i_max} for the isolated stack and x_{b_max} for the BDW-plume. We than construct a point-to-point mapping between the GLCP in presence of a building and the GLCP for the isolated stack:

$$f : x_b \rightarrow x_i : \begin{cases} C_i(x_i, 0, 0) = C_b(x_b, 0, 0) \\ sign(x_i - x_{i\_\max}) = sign(x_b - x_{b\_\max}) \end{cases}$$

As a result each point of the BDW-GLCP before Cmax is mapped to that point of the GLCP of the isolated stack before Cmax that has the same concentration C, and the same is done for the GLPC parts after Cmax. This mapping defines a function Δ(xb) which we have computed for each measured GLCP. Δ(xb) is used as a (lower bound of a) measure for the accelerated plume growth due to building induced turbulence. Δ(xb) is a sum of functions whose coefficients have been determined.
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 $\sigma_y(x)$ and $\sigma_z(x)$ when calculating the ground-level concentration. In the Briggs plume rise equations, only that part of the plume rise between 2 xb*and x_{final} 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 R^2=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 (GLC-profiles) 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 Thompsons 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 GLC-profiles 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 GLC-profiles 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**'.

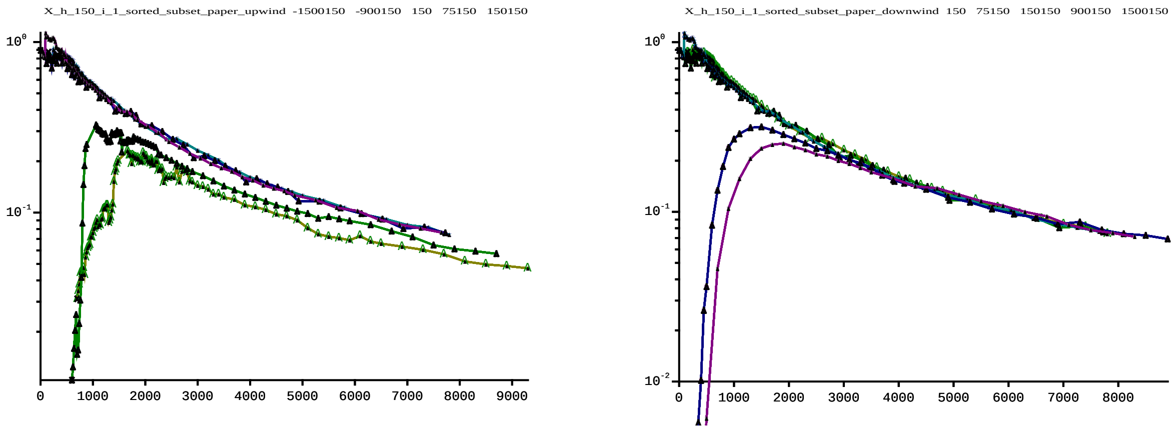


Fig. 1: Measured GLC-profiles for emissions through stacks of equal height Hb located on respectively the top of a cubic building (common curves on both graphs) and at positions Xs equal to 10 Hb and 6 Hb upwind (left) and downwind (right) of the upwind side of a cubic building.

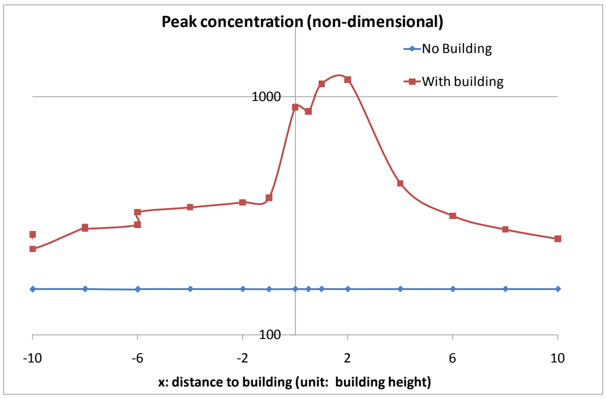


Fig.2 Peak values of measured GLC-profiles versus the position of stack to building for the cubic building, Hs=Hb.

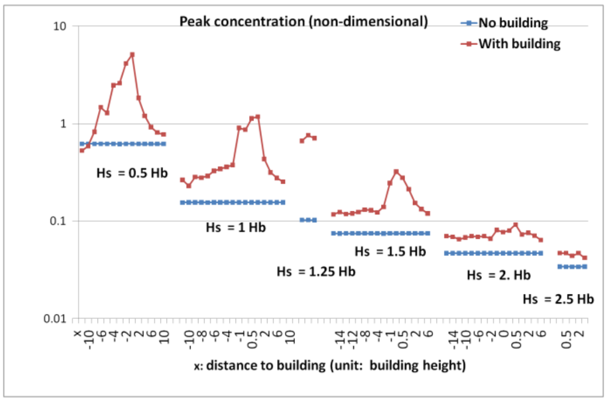


Fig.3 Peak values of GLC-profiles versus distance of stack to building for all the measurements with cubic building

THE VIRTUAL PLUME

The GLC-profiles $C(x, H_S)$ measured by Thompson (1993) can be reproduced by the Gaussian diffusion equation:

$$C(x,H_S) = \frac{Q}{\pi \; u(H^*)\sigma_y(x^*)\sigma_z(x^*)} \exp\left(-\frac{1}{2} \left\{ \frac{H^*}{\sigma_z(x^*)} \right\}^2 \right) \tag{1}$$

where:

- Q is the source term;
- u is the wind speed profile measured in the empty wind tunnel:
  - $u(z) = 2.2\,(z/10)^{0.136}$ or $u(z)=0.35\,ln[(z-2.62)/0.015]$ (2)
- $\sigma_y(x)$ and $\sigma_z(x)$ are the horizontal and vertical dispersion parameters. Cosemans and Lefebvre (2010) derived following expressions for the wind tunnel:
  - $\sigma_y(x)=(\,0.418 - 0.0001(4.5H + 500))x^{0.796}$ (3)
  - $\sigma_z(x)= (0.382 + 0.0001(4.5H-0.0005(H-150)^2))x^{0.711}$ (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:

$$x_0 = x + Displacement \quad (5.1)$$
$$x_1 = x_0 + Before(x_0) \quad (5.2)$$
$$x^{*} = x_1 + After(x_1) \quad (5.3)$$

Before and *After* refer to X_{C_max}, the location of the maximum ground-level concentration, given by:

$$X_{C\_max} = 17.65 * (H_{final}) \quad (6)$$

where H_{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_max}.
After(x_1) increases from 0 to A_f over the interval between $0.9\ X_{C\_max}$ and min(6* 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_{final} at X_{C_max}.

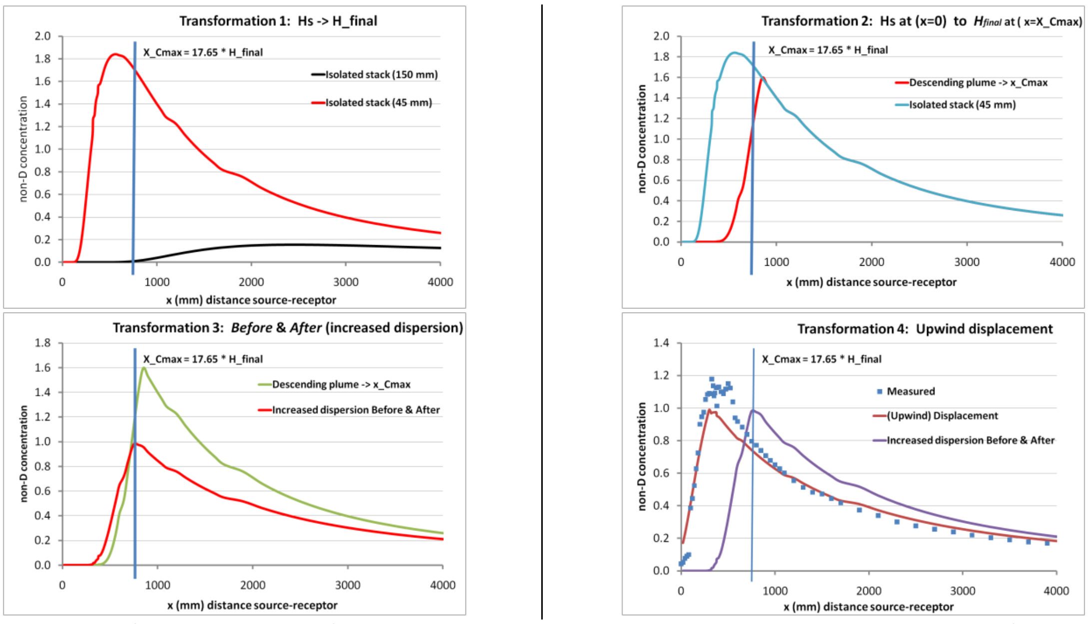


Fig.4: Reproduction of a measured GLC-profile (Cubic building, Hs = Hb, Xs = 2Hb, Hb=150mm) with H_{final}=45mm, Before = 434 mm, After = 175 mm and Displacement = -428 mm.

HOW IT WORKS: AN EXAMPLE

Fig. 4 illustrates how these definitions produce a GLC-profile for the case Xs=300 mm, Hs=Hb=150 mm. The parameter values used are H_{final}=45mm, *Before* = 434 mm, *After* = 175 mm and *Displacement* = -428 mm. In the first transformation (upper left panel of Fig 4.), the stack (black concentration profile) is replaced with a stack with the height H_{final} (red concentration profile). Thereafter (upper right panel of Fig. 4), the height of the plume axis is set to decrease between the stack and x_Cmax (blue concentration profile => red concentration profile). Thirdly (lower left panel of Fig. 4), extra in-mixing is added to the plume, both before the maximum concentration and after the maximum concentration (green concentration profile => red concentration profile). Finally (lower right panel of Fig. 4), the concentration profile is displaced (purple concentration profile => red concentration profile). The point X_{C_max} (Eq.6) is very important in the computational scheme. The fact that *Before* and *After* both increase near X_{C_max} expresses the intense mixing of ambient air in the plume near the location of the peak GLC. Fig. 4 also illustrates that the 'final virtual plume height' is only a construction aid. The peak value of the reproduced profile is about 1 (non-D concentration), while the peak concentration of an isolated stack of height H_{final} is 1.8.

CURVE FITTING OF PARAMETERS

Equation (1) can be evaluated for each of the measured GLC-profiles provided we know the values of H_{final}, *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_{final}, *Displacement*, B_f and A_f are given by an expression of the form:

$$(A_1G_{1,Hs} + B_1G_{2,Hs} + C_1)(G_{3,Xs}) + (A_2G_{4,Hs} + B_2G_{5,Hs} + C_2)(G_{6,Xs}) \quad (7)$$

where A_i, B_i and C_i are constants and $G_{i,Hs/Xs}$ is a Gaussian function with mean μ_i and spread σ_i. μ_i and σ_i can be functions of Hs and/or Xs.

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.)

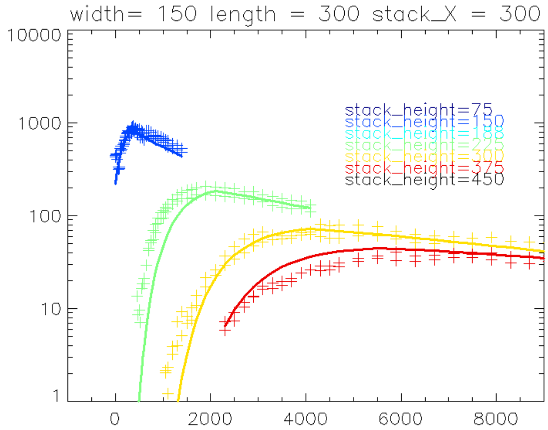


Fig.5: The reproduces GLC-profiles often fit nicely between GLC-profiles that have been measured twice, indicating that noise-fitting has been avoided by fitting curves through the optimal values for the parameters H_{final}, Displacement, B_f and A_f. +s denote the measurements, the lines show the model results.

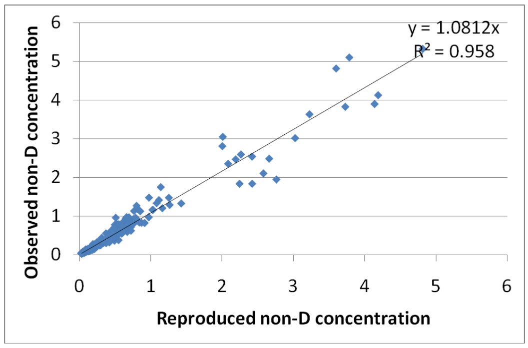


Fig.6: Scatter diagram peak concentration observed versus model.

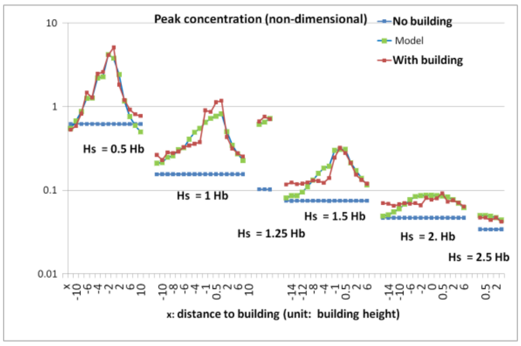


Fig. 7: The same as Fig.3, but with model predictions added.

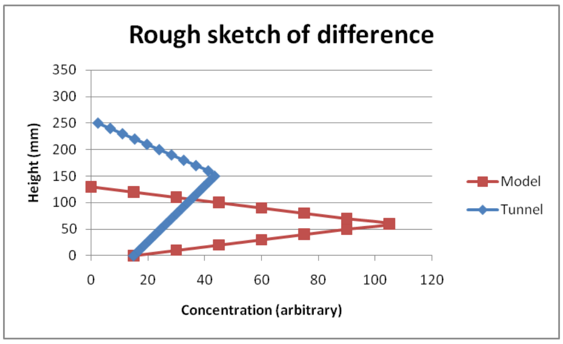
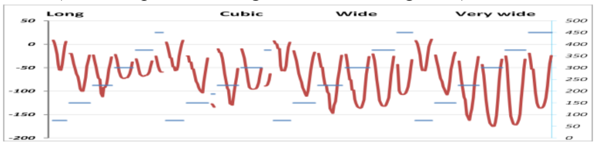
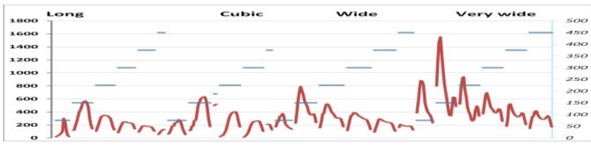


Fig. 8:Vertical concentration profile (simplified.)

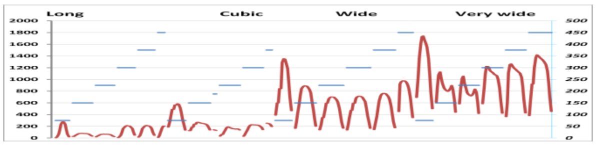
A: Δh (left axis: parameter, right axis: stack height Hs)



B: Before



C: After



D: Displacement

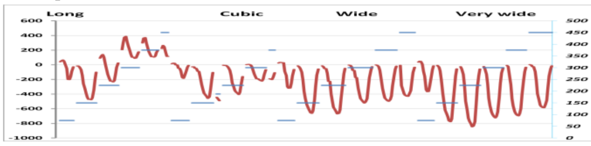


Fig. 9: Graphical representation of the outcome of Eq.7 for the parameters H_{final},(only Δh given), Displacement, Before and After for each of the four building types used by Thompson.

VALUES OF THE PARAMETERS

Fig. 9 shows the smoothed values of the parameters H_{final} *(shown:* $\Delta h = H_{final} - Hs$*), 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 Hs, 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 ***Δh*** is roughly 150 mm (that is: building height), except when the stack is low; it is 50 mm for Hs=75 mm and 100 mm for Hs=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, Δh 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:

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

The Δh component of H^* is found to be wind speed dependent. Including Eq. 8, Δh_{field} is currently:

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

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.

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