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SPATIAL AND TEMPORAL CONCENTRATION DISTRIBUTIONS IN URBAN AREAS

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Abstract: Mathematical models are frequently applied to predict the concentration field in urban environments. In emergency situations involving airborne hazardous materials, first responders often rely on models based on distribution functions (such as the Gaussian models) to define the danger zone and support the rescue. Above flat open terrain and homogeneous roughness, distribution functions are applied successfully to describe the spatial concentration distributions. However, due to turbulence caused by the city structure, it is not straight forward that the approximating functions applied for flat open terrain and homogeneous roughness give a reasonable estimation of the concentration distribution in an urban area. Results of boundary-layer wind tunnel measurements from the COST Action ES1006 were investigated. The dataset contains two different urban setups: a semi-idealized urban structure (Michelstadt) and the model of an existing city centre (CUTE). The lateral and longitudinal profiles of mean concentrations are approximated by the Gaussian dispersion equation. The results help to improve and identify the strengths and weaknesses of predicting the concentration field based on distribution functions in urban areas. The parametrised Gaussian dispersion equation fits well on the mean concentration profiles, however the maximum concentration is not aligned with the source parallel to the main wind direction.

Key words: *Gaussian distribution, urban dispersion, wind tunnel*

INTRODUCTION

Due to urbanisation, accidental releases inside cities affect more and more people. First responders often rely on results from numerical models to predict the dispersion of hazardous materials. Due to its instantaneous results and simplicity, the Gaussian plume model is often used for this purpose.

According to Hanna et al. (1982), the Gaussian model originates from Sutton (1932), Pasquill (1961, 1974) and Gifford (1961). The generalized Gaussian dispersion equation for a continuous point-source plume (not considering vertical dispersion reflection due to inversion) has the form

$$C(x,y,z)=\frac{Q}{u}\frac{1}{2\Pi\sigma_y\sigma_z}\exp\left(\frac{-y^2}{2\sigma_y^2}\right)\left[\exp\left(\frac{-(z-H)^2}{2\sigma_z^2}\right)+\exp\left(\frac{-(z+H)^2}{2\sigma_z^2}\right)\right], \qquad (1)$$

where C is the concentration, x is the coordinate parallel to the direction of the approach flow, y is the horizontal coordinate perpendicular to the direction of the approach flow and z is the vertical coordinate (Beychok, 1994). The coordinates of the source are $(0,0,H)$. Q stands for the release flow rate, U is the mean wind velocity component parallel to the main wind direction of the approach flow at H height, σ_y is the horizontal dispersion coefficient and σ_z is the vertical dispersion coefficient. In case of ground-level point sources ($H=0$), equation (1) can be simplified to

$$C(x,y,z)=\frac{Q}{u}\frac{1}{\Pi\sigma_y\sigma_z}\exp\left(\frac{-y^2}{2\sigma_y^2}\right)\exp\left(\frac{-z^2}{2\sigma_z^2}\right). \qquad (2)$$

Among other limitations, the Gaussian dispersion equation applies only if the turbulence is homogeneous throughout the plume (Beychok, 1994). However, when an airborne pollutant is released in a built-up area, the city geometry causes inhomogeneity in the turbulence, therefore the applicability of the Gaussian dispersion equation is not straightforward.

To investigate the dispersion characteristics in an urban environment, wind tunnel measurements were carried out. The dataset contains two different urban setups: a semi-idealized urban structure (Michelstadt) and the Complex Urban Terrain Experiment (CUTE). The measurements serve as validation test cases used in the frame of the COST Action ES1006 to evaluate and improve local-scale emergency response tools (Baumann-Stanzer et al., 2015). Based on the datasets, the concentration profiles parallel and perpendicular to the approach flow direction were investigated.

EXPERIMENTAL SETUP

The wind tunnel measurements were carried out in the “WOTAN” boundary-layer wind tunnel located in the Environmental Wind Tunnel Laboratory in Hamburg. The tunnel has an 18 m long and 4 m wide test section. The height is adjustable between 2.75 and 3.25 m. The boundary layer is generated by turbulence generators and roughness elements placed upwind of the test section.

Results of two wind tunnel measurement campaigns are evaluated to investigate urban dispersion. Michelstadt (Figure 1) is a 1:225 model of a semi-idealized urban geometry (Hertwig et al., 2012). The model has aspect ratios, building heights and street widths typical for many Central-European cities (Di Sabatino et al., 2010). The CUTE measurements (Figure 2) were carried out within the 1:350 model of the downtown area of a typical Central European city (Baumann-Stanzer et al., 2015).

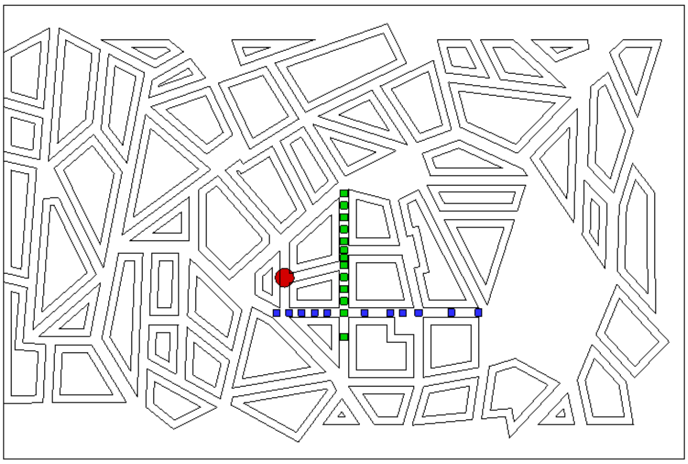

Figure 1. Model of Michelstadt with the selected measurement profiles. The source is indicated with a red circle and the measurement locations are marked with blue and green squares.

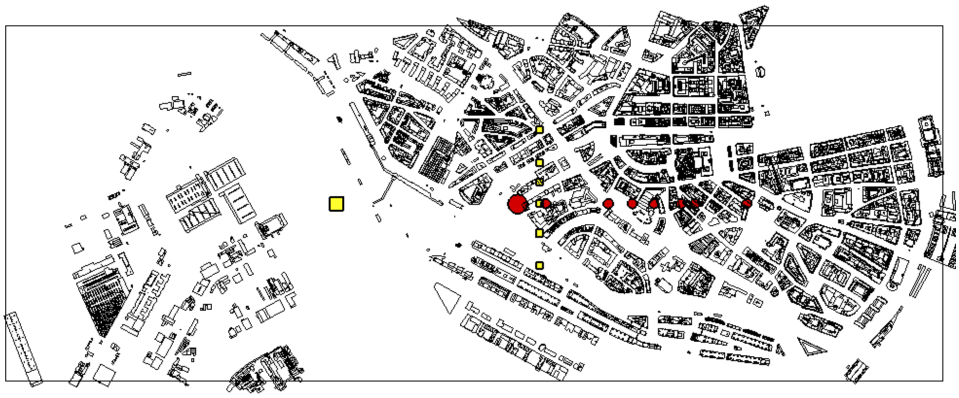

Figure 2. Model of the CUTE test case. The sources are indicated with large symbols, and the corresponding measurement locations are marked with smaller squares and circles.

To model urban dispersion, ethane tracer gas was released from ground-level point sources represented by fast solenoid micro-valves. The concentration was recorded with high temporal resolution by a fast-Flame Ionisation Detector. The uncertainty of the results was determined based on repetitive measurements.
The results are converted to dimensionless concentration values using the formula

$$C^* = \frac{C U_{ref} L_{ref}^2}{Q}, \tag{3}$$

where C^* is the dimensionless concentration, C is the measured concentration, U_{ref} is mean reference wind speed, L_{ref} is the reference length and Q is the flow rate of the release.

The measurement results form a dataset to evaluate numerical models in the frame of the COST Action ES1006 (Baumann-Stanzer et al., 2015). The main purpose of the measurements was to provide a high-quality dataset optimal for the validation of emergency response tools applied during an accidental release in an urban area. For this paper, the data is evaluated to investigate dispersion characteristics relevant for urban areas. The concentration distribution is investigated based on the mean concentration field of continuous release dispersion.

RESULTS

Four concentration profiles were selected for this paper, a lateral (constant-y) and a longitudinal (constant-x) profile for each dataset. The selected measurements were carried out at pedestrian-level height.

Parametrised Gaussian equations were fitted on the measured mean dimensionless concentration profiles. For lateral profiles equation (4) and for longitudinal profiles equation (5) were fitted. The parameters *a*, *b*, *c*, *d* and *e* were approximated using nonlinear least squares method. The fitted functions are plotted in Figure 3.

$$C^*(x) = \frac{a}{\Pi b x^c d x^e} \tag{4}$$

$$C^*(y) = \frac{a}{\Pi bc} \exp\left(\frac{-(y-d)^2}{2b^2}\right) \exp\left(\frac{-(z)^2}{2c^2}\right) \tag{5}$$

While deriving equation (4) and (5), additional assumptions were considered to those already applying to the Gaussian dispersion equation (Beychok, 1994). For equation (4) the shape of mean dimensionless concentration profile is expected to be similar throughout the y axis and the height of the measurement points is neglected. The horizontal and vertical dispersion coefficients ($\sigma_y = bx^c$ and $\sigma_z = dx^e$ in equation 4) are modelled as power functions of the distance from the source as suggested originally by Smith (1968). For equation (5), an extra degree of freedom is introduced with the *d* parameter, allowing the profile to take its maximum independently from the source location. Whereas the Gaussian dispersion equation assumes that the plume centreline is aligned with the source parallel to the main wind direction.

The Gaussian distribution fits well to the lateral and longitudinal concentration profiles for both test cases (Figure 3). However, the approximated maximum concentrations of the lateral profiles are not aligned with the source locations due to the influence of the city geometry.

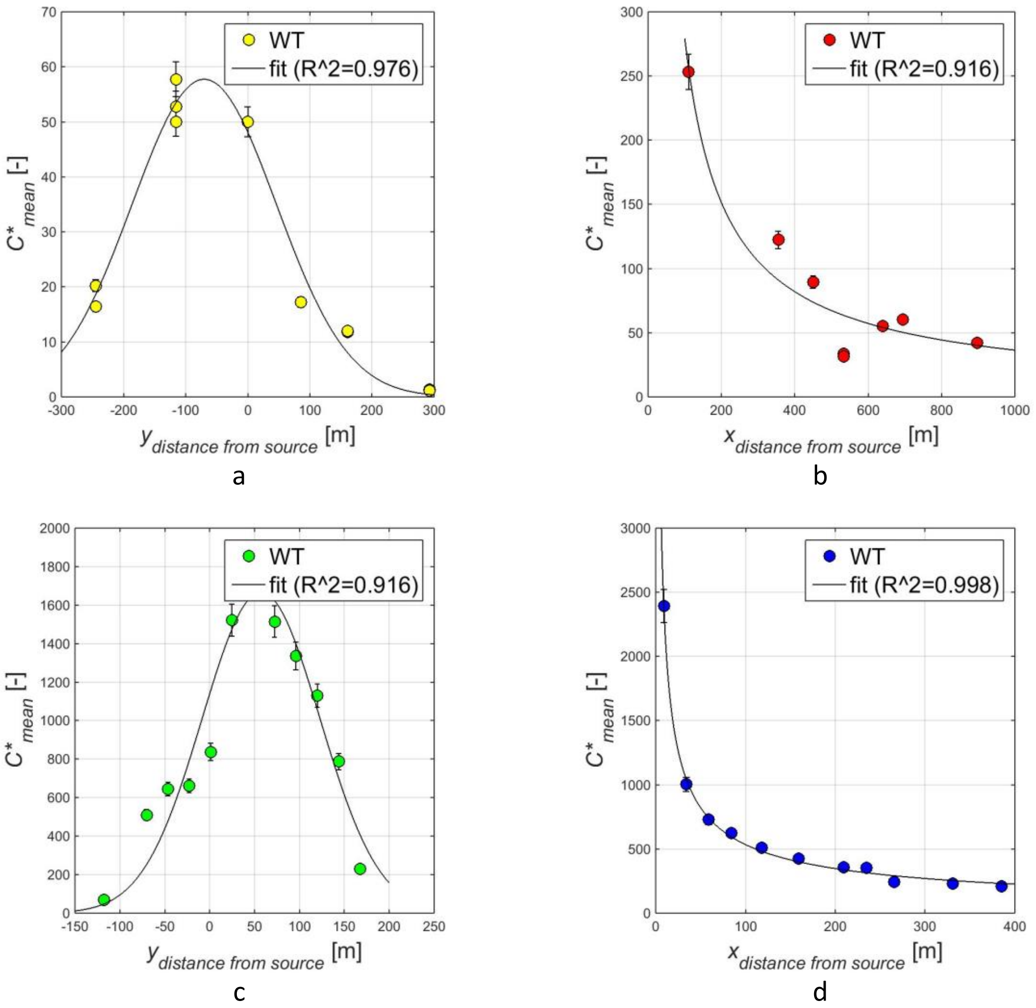

Figure 3. Concentration profiles measured in Michelstadt (a and b) and CUTE (c and d). Equation 4 is fitted on the lateral profiles (a and c) and equation (5) is fitted on the longitudinal profiles (b and d). The goodness of the fit is indicated by the R^2 measure, WT stands for wind tunnel results.

CONCLUSIONS

During emergency situations involving accidental releases, first responders often rely on models based on distribution functions (such as the Gaussian model) to support the rescue. When the turbulence is homogeneous, the distribution functions are applied successfully to describe the mean concentration field. However, due to inhomogeneous turbulence caused by the city structure, it is not straight forward that the Gaussian dispersion equation applied for flat open terrain or above homogeneous roughness gives a reasonable estimation of the concentration distribution in an urban area.

Results of boundary-layer wind tunnel measurements from the COST Action ES1006 were investigated. Concentration profiles of two datasets were studied: a semi-idealized urban structure (Michelstadt) and the model of an existing city centre (CUTE). The lateral and longitudinal profiles of mean concentrations are approximated by the Gaussian dispersion equation. The results show that the parametrised Gaussian dispersion equation fits well on the lateral and longitudinal mean concentration profiles. However, the maximum concentration is not aligned with the source parallel to the main wind direction due to the influence of the urban structure.

The results show that the distributions described by equations (4) and (5) fit well to the selected measurement profiles. However, this does not necessary imply that a Gaussian model would give such a good fit to the measurements. The parameters of equations (4) and (5) were approximated by non-linear regression analysis to fit to the results. Whereas the Gaussian model calculates the concentration profiles using only the boundary conditions of the measurements.

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