VALIDATION OF GAUSSIAN MODELS USING WIND TUNNEL EXPERIMENTS AND NUMERICAL SIMULATION

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Abstract: The validation of a Gaussian fluctuating plume model is presented. The model includes the effects of the presence of obstacles based on the approach of the PRIME model and is here employed to predict dispersion of an odorant compound. Due to its non-steady formulation, the model is able to predict the concentration peaks, as well as the intermittency factor and frequency of occurrence of odour events. The model results are compared to wind tunnel measurements and to a computer fluid dynamics simulation using the Large Eddy Simulation technique.

Key words: *odour, dispersion, obstacle, Gaussian, fluctuating plume*

INTRODUCTION

Due to the interest in dispersion in urban areas, a considerable amount of work has been carried out concerning dispersion around buildings, i.e. Petersen, R. L. and Carter, J. J. (2006); Sironi, S. et al., (2011). Odour sources have become very familiar in urban areas as the cities enlarge their built areas around wastewater treatment plants. Dispersion models, which account for the presence of obstacles and odour sources, can vary from simple Gaussian models to complex numerical models.

Gaussian models are widely used for regulatory purposes due to their simplicity and relative accuracy. These models have been modified to account for effects of an obstruction on the spreading of a plume by changing the characteristics of the source or enhancing the dispersion parameters and adjusting the plume centreline. Few Gaussian models have included parameters for the assessment of odour impact, such as peak concentration (maximum averaged concentration over periods shorter than 1 hour) and frequency of occurrence of peak concentrations during a time interval (De Melo Lisboa, H. et al., 2006; Schauberger, G. et al., 2000).

Numerical models are based on the numerical solution of the transport equations and can provide concentration, velocity and turbulence fields. However, it is important to emphasise that these models are more appropriate to research and development applications than to operational use in hazard assessment and air quality control. The description of atmospheric turbulence is still troublesome, since the available computational power is still not sufficient to solve all scales of turbulence in the fluid flow. The Large Eddy Simulation (LES) has been largely used in the literature to model turbulent flow around obstacles and shown to produce good results (Salim, S. M. et al., 2011). This turbulence model can provide information of concentration fluctuation that can be used to calculate peak concentrations and its frequency of occurrence.

This work presents the validation of a Gaussian fluctuating plume model which includes the effect of the presence of obstacles and allows for the prediction of peak concentration as well as its frequency of occurrence. A case study is presented to simulate the dispersion of a pollutant that is emitted from the top of a complex geometry building. The Gaussian model results are compared to wind tunnel data as well as numerical simulation results obtained using the LES.

MODEL DESCRIPTION

Fluctuating Plume Model

The Fluctuating Plume Model (FPM) was proposed by Gifford, F. (1959), as a derivative of the traditional steady state gaussian plume model, where the vertical and horizontal levels of concentration of an emitted pollutant downwind of the source followed a Gaussian distribution; but in the FPM, the plume fluctuates as a result of wind meandering and velocity fluctuation. The plume centreline positions as well as the dispersion inside the follows a Gaussian distribution so that the long term dispersion parameter of the Gaussian model and the FPM dispersion parameters are related by Equation 1.

$$\sigma_c{}^2 = \sigma^2 + \sigma_p{}^2 \qquad (1)$$

Where σ is the long term dispersion parameter, σ_c is the standard deviation of the plume centreline positions and σ_p is the plume segment dispersion parameter. The horizontal and vertical σ_{yp} and σ_{zp} parameters are calculated following Högstrom, U. (1972). Based on the dispersion coefficients, FPM randomically generates a series of instant plume positions which results in a concentration series for each receptor. These concentration series allows the determination of useful parameters for odour impact assessment, such as the (a) intermittency factor (defined as the percentage of time during which the concentration lies above or below a certain threshold), (b) the peak-to-mean concentration ratio and also (c) the frequency of occurrence of odour events. To determine the frequency of occurrence of odour events, emission rate should be expressed in terms of odour units concentration and volumetric flow rates; the concentration series at a receptor can then be classified according to odour intensity (Mussio, P. et al., 2001; De Melo Lisboa, H. et al., 2006).

PRIME model

The **P**lume **Ri**se **M**odel **E**nhancements model (PRIME) (Schulman, L. L., Strimaitis, D. G. and Scire, J. S., 2000) was proposed for assessing the effects of obstacles in the velocity field and its consequences in pollutant dispersion. It was first included in the ISC3 regulatory model and is currently used in AERMOD and Calpuff regulatory models. The model includes the effect of the obstacle in changing the streamlines slopes and, as a consequence, causing plume elevation and/or downwind, and capture by the obstacle wake. A numerical plume rise is used in order to determine the plume trajectory in the modified field. Concentration calculation takes into account the effect of the fraction of plume captured by the obstacle cavity, which is re-emitted to the obstacle far wake.

EXPERIMENTAL SETUP

Fluctuating Plume Model

The simulation consisted on atmospheric flow and dispersion around a complex geometry building, located in a flat terrain in the field (Figure 1). Atmospheric stability was neutral. The simulated case is based on a study by Aubrun, S. & Leitl, B. (2004), involving wind tunnel experiments with dataset available at the Hamburg University website (CEDVAL, 2002). Similar incoming velocity profiles were employed in FPM and on the CFD simulation.

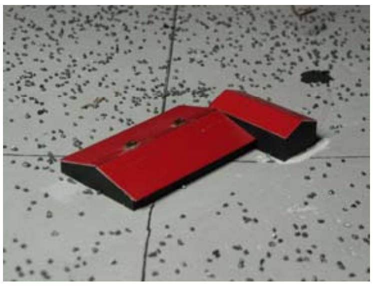

Figure 1: model of the obstacle used in the wind tunnel experiments (CEDVAL, 2002)

Large Eddy Simulation

The large eddy simulation is a technique to include turbulence effects on the solution of the flow governing equations. The concept is based on space filtering, where only the larger scales of turbulence are directly solved, while the smaller scales are modelled. Being dependant on flow geometry, the larger scales present higher energy levels, thus influencing the transport of the flow properties (Ferziger, J. H. & Peric M, 2002). The smaller scales are isotropic, have weaker energy levels and so are easily modelled. As a transient simulation is employed, it is possible to assess peak concentrations and fluctuation data. The simulated domain of 45H x 13H x 6H (LxWxH), where H is the average height of the obstacle (8.8 m), was divided into a 5,235,563 point grid of more than 30 million tetrahedrycal elements. The simulation was solved with the finite volume method using the ANSYS CFX commercial software.

RESULTS

Concentration

Average concentration results are presented in figure 2a, 3a and 3b for an averaging time of 2000 minutes. Concentration results are normalized by the concentration measured at the source. Receptor height is 1.6 m above ground. Figure 2a shows the downwind concentration variation. Both FPM and CFD results are within the same order of magnitude of the wind tunnel results, but overpredicted the concentration. As expected, concentration decayed with distance within the obstacle wake. The highest average concentration predicted by the FPM model was observed just after the obstacle recirculating cavity, which seems to agree with the wind tunnel results, although the lack of other monitoring points within the cavity in the wind tunnel experiment does not give a detailed behaviour of the tracer gas dispersion in that region. The same is true for the CFD results, which show the maximum concentration occurring inside the cavity. FPM predicted concentrations within the cavity did not show great variation as the model approach, based on PRIME, considers concentration to be verticaly mixed inside the recirculation zone and also employs the same value for the dispersion coefficients within the cavity limits. The predicted average concentration peak near x=50 m is situated on the transition zone, where the cavity start to act as a volume source emitting through the obstacle wake.

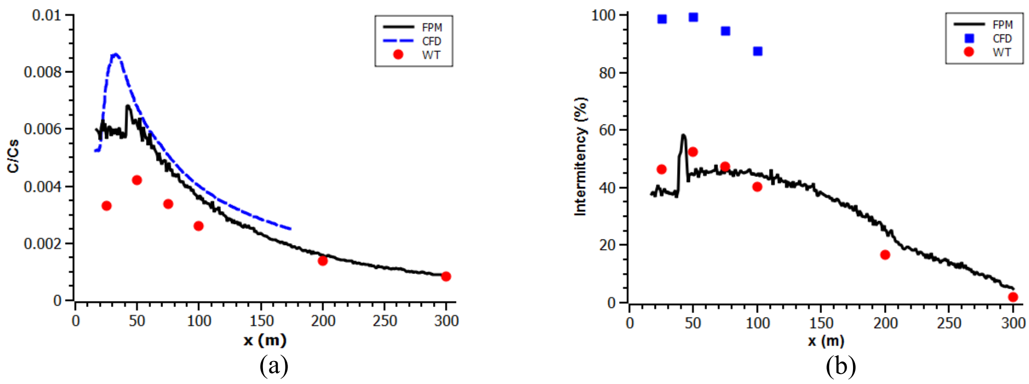

Figure 2: (a) non-dimensional average downwind concentration levels (z=1.6 m); (b) downwind intermitency levels (z=1.6 m).

Figure 3 shows the lateral concentrations observed at x=50 m (Figure 3a) and at x=100 m (Figure 3b). Both FPM and CFD results were within the same order of magnitude. Maximum concentrations are predicted at the centreline plume location (y≈0 m) by FPM and CFD, but both overpredicted the wind tunnel results. Lateral concentration decay values predicted by CFD were much closer to WT than what is predicted by FPM. Results show CFD better predicts the effect of the obstacle on the flow and dispersion. FPM results suggest the plume is much wider than what is observed in WT and predicted by CFD, possibly indicating an overprediction of the lateral dispersion coefficients and thus, higher levels of fluctuation of the plume centerline. The same trend is observed at x=50 and x=100m. This can be explained by the fact that FPM “sees” the obstacle as a “block” while CFD and WT shows the effect of the obstacle complex geometry.

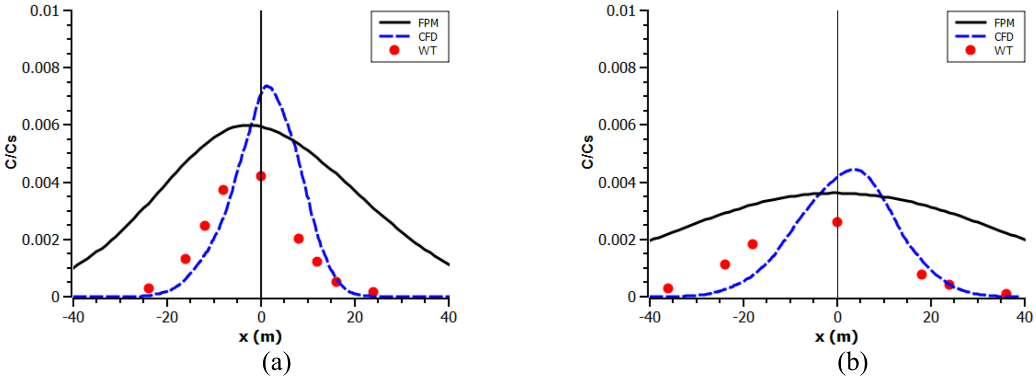

Figure 3: (a) non-dimensional average lateral concentration levels (x=50 m, z=1.6 m); (b) non-dimensional average lateral concentration levels (x=100 m, z=1.6 m).

Intermitency

In the present work, intermittency is defined as the percentage of time where the concentration stays above a defined threshold (Aubrun, S. & Leitl, B., 2004). Following the WT experiments, the chosen concentration threshold was 0.25% of the average concentration measured at the source (Cs), simulating the detection threshold of an odorant compound. Intermitency results are presented in figures 2a, 4a and 4b. Figure 2a shows downwind intermittency levels observed at z=1.6 m. FPM predicted intermittency levels were very close to WT observed results. The location of the highest intermittency level predicted by FPM is at the beginning of the wake, just after the cavity. Intermitency levels decay with downwind distance, in accordance with the average concentrations decay. It can be noted that although average concentrations observed at downwind distances greater than about 150 m are below the chosen concentration threshold fluctuation would still produce odour events which can cause nuisance to a nearby receptor. This fact demonstrates the importance of modelling plume fluctuation. Figure 1b also indicate that intermittency levels are greatly overpredicted by CFD, even at location where the predicted concentration is close to WT observed levels. This result indicates the CFD plume centreline position fluctuation is much less intense than WT and FPM. In fact, the analysis of the FPM and CFD concentration series at 4 selected points located at x=25.2 m, 50 m, 75.2 m and 100 m (y=0 and z=1.6 m) shows concentration fluctuation intensity levels are between 4 and 5 times higher in FPM than CFD. As the concentration fluctuation intensity is directly related to turbulence intensity, results indicate CFD turbulence levels are much lower than observed in WT at y=0. This behaviour was not observed in the lateral intermittency distribution (figures 4a and 4b), where CFD results were close to WT levels, indicating the lateral influence of the obstacle is correctly reproduced. Both at x=50 m and at x=100 m, WT lateral intermittency levels were overpredicted by FPM. All results indicate that even at lateral locations where the average concentration is below the threshold concentration peaks are still noticeable.

CONCLUSION

The present work proposed a fluctuating plume Gaussian model to simulate flow and dispersion around a complex geometry obstacle. Results were compared to wind tunnel experiment results, as well to a computer fluid dynamics simulation using the large eddy simulation technique. The effects of the obstacle were included in FPM based on the approach used in the PRIME model. Results for downwind and lateral concentration distribution, as well as intermittency distribution are presented for a receptor located at a height of 1.6 m, similar of average nose level. Downwind average concentration results showed good agreement between FPM, CFD and WT; although the WT concentrations were overpredicted by FPM and CFD, the results were on the same order of magnitude. The maximum average concentration predicted by FPM was at a similar position than observed at the WT experiment. Lateral concentrations observed in WT were also overpredicted by FPM and CFD, with CFD results closer to WT. The lateral extent of the obstacle disturbance to the flow is overpredicted by the FPM. These findings were confirmed by intermittency results, where WT and CFD results showed a similar behaviour, although the centreline intermittency was largely overpredicted by CFD results. Downwind intermittency results showed good

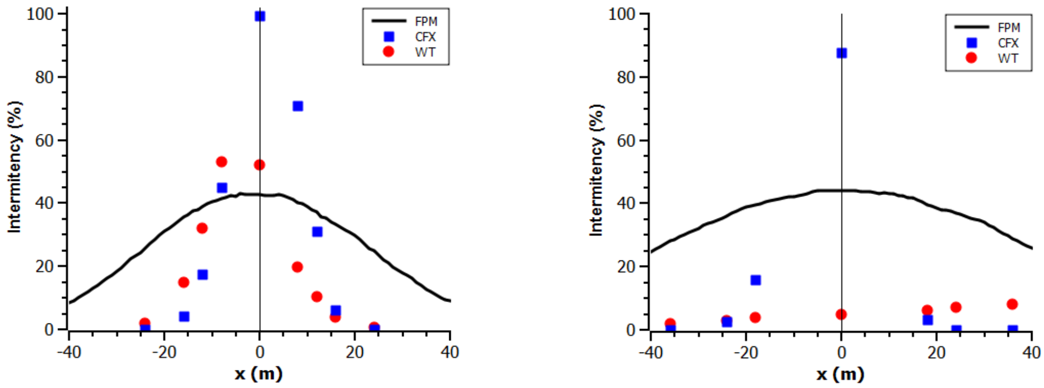

Figure 4: (a) lateral intermitency levels (x=50 m, z=1.6 m); (b) lateral intermitency levels (x=100 m, z=1.6 m).

agreement between WT and FPM results. Results indicate FPM is a viable alternative to assess dispersion around obstacles, especially when evaluating centerline and close to ground parameter, as this is where maximum values are expected. Further research should be done with FPM, especially in terms of modelling lateral behaviour, as well as the effect of different atmospheric stability conditions.

REFERENCES

Aubrun, S.; Leitl, B. (2004) Unsteady characteristics of the dispersion process in the vicinity of a pig barn. Wind tunnel experiments and comparison with field data. Atmospheric Environment, 38, 81-93.

COMPILATION of Experimental Data for Validation of Microscale Dispersion Models – CEDVAL. (2002). Available at: < http://www.mi.uni-hamburg.de/CEDVAL_Validation_Data.427.0.html>. Acessed in March, 20, 2013.

De Melo Lisboa, H. ; Guillot, J. M. ; Fanlo, J. L.; Le Cloirec, (2006) P. Dispersion of odorous gases in the atmosphere — Part I: Modeling approaches to the phenomenon. Science of the Total Environment. 361, (1-3), 220–228

Ferziger, J. H.; Peric, M.. Computational methods for fluid dynamics. (2002) Third Edition. Springer. Germany, 2002.

Gifford, F. Statistical properties of a fluctuating plume dispersion model. (1959) Advances in Geophysics, 6, 117-137.

Hogström, U. A Method for predicting odour frequencies from a point source. Atmospheric Environment. (1972) 6, 103-121.

Mussio, P., Gnyp, A. W., Henshaw, P. F. A fluctuating plume dispersion model for the prediction of odour-impact frequencies from continuous stationary sources (2001) Atmospheric Environment 35 (16) 2955-2962.

Petersen, R. L.; Carter, J. J. Evaluation of AERMOD/PRIME For Two Sites with Unusual Structures. (2006) A&WMA 99th Annual Conference, June 20-23

Salim, S. M.; Buccolieri, R.; Chan, A. & Di Sabatino, S. Numerical simulation of atmospheric pollutant dispersion in an urban street canyon: Comparison between RANS and LES. (2011) Journal of Wind Engineering and Industrial Aerodynamics 99 (2-3) 103—113

Schauberger G, Piringer M, Petz E. Diurnal and annual variation of the sensation distance of odor emitted by livestock buildings calculated by the Austrian odor dispersion model. (2000) Atmospheric Environment 34, 4839 – 51.

Schulman, L. L.; Strimaitis, D. G. & Scire, J. S. (2000), Development and evaluation of the PRIME Plume Rise and building downwash model, *Journal of the Air & Waste Management Association* **50**(3), 378-390.

Sironi, S.; Capelli, L.; Centola, P.; Del Rosso, R. & Pierucci, S. (2010), Odour impact assessment by means of dynamic olfactometry, dispersion modelling and social participation, Atmospheric Environment 44(3), 354-360.