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CHARACTERIZATION OF TRANSIENT DISPERSION PROCESSES IN AN URBAN ENVIRONMENT

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Abstract: Validating LES-based flow and dispersion models for the purpose of predicting transient flow and dispersion phenomena is more demanding than validating RANS-based codes. Since the model output is no longer related to stationary or quasi-stationary boundary conditions, and since the model results are not restricted to mean flow and average dispersion patterns, an evaluation of the model based on mean results is no longer adequate. A more sophisticated but also more complex validation approach based on statistically representative ensembles is required. Reference data is needed which reliably identifies mean as well as extreme values of concentration, dosage and cloud travel times for a given dispersion scenario. An example of how systematic wind tunnel measurements can characterize transient dispersion processes of puffs in a complex urban environment is given.

***Key words:** puff dispersion**,** urban dispersion, wind tunnel, emergency response tool, LES validation.*

INTRODUCTION

Dispersion processes in an urban environment are highly complex. Numerical simulations that predict these processes require substantial computational effort. In the past simpler models such as empirical (Gaussian) models, diagnostic models (which use only the mass conservation equation) or CFD models with full parameterization of turbulence, i.e., Reynolds-averaged Navier–Stokes (RANS) codes were used for these complex tasks. Nowadays increasing computer power enabled the possibility to use Large Eddy Simulation (LES) models for urban flow and dispersion simulations. Sagaut P. (2005) states that Large Eddy Simulations are an effective intermediate approach between Direct Numerical Simulations (DNS) and the RANS methods. A basic requirement of any numerical model is the validation. Validation data for numerical models are not just any experimental data; they must fulfill certain requirements with respect to completeness, spatial and temporal resolution, accuracy, representativeness and documentation of the measured results (Schatzmann M. and B. Leitl, 2002). If these requirements are not met, too many degrees of freedom remain in the set up of numerical model runs. A wide variety of numerical results can be generated with reasonable assumptions for the input data, with the consequence that a solid conclusion concerning the model quality cannot be reached. Hence validation datasets that match the complexity of specific groups of models are needed. In order to validate an urban LES simulation validation data is required that contains data of flow and turbulence fields in combination with concentration fields measured with high resolution in space and time. Field measurements do not fulfill these high validation requirements, unless they have been carried out over long periods of time with many repetitions of individual situations. In the laboratory, however, and under certain limiting conditions, such datasets can be generated under carefully controlled conditions in well- equipped boundary layer wind tunnels.

The results presented here were obtained as part of a pilot study initiated by the German Federal Office of Civil Protection and Disaster Assistance to test the LES-based model FAST3D-CT and the emergency response tool CT-Analyst using Hamburg, Germany as a pilot city. The models, developed by the Naval Research Laboratory (NRL), were successfully verified based on several field and laboratory data sets compiled for complex urban geometries which are typical for cities in the US. Dense built-up areas with tall buildings and a substantial local variability in building height are characteristic features of US urban areas. The question however was how the tool would perform in other urban environments such as typical European cities. Hamburg offers a variety of typical European urban features as well as some very specific threats resulting from a large harbor area included in the bounds of the city. The focus of the study is on validating the size of estimated danger zones and cloud travel time in a typical European city.

THE FAST3D-CT AND CT-ANALYST MODEL

FAST3D-CT, a detailed physics-based numerical LES-model (Boris J., 2002), was developed at the Naval Research Laboratory to accurately predict plume evolution and the contamination footprints resulting from these releases. It is a general-purpose fully 3D computational fluid dynamics (CFD) model for the simulation of transport processes in complex urban geometries. It is based on the high-resolution, time accurate Flux-Corrected Transport algorithms developed at NRL.
The model output from the FAST3D-CT CFD calculations are summarized and distilled into memory efficient, time-independent Dispersion Nomograph^{TM} data sets. These are interpreted and evaluated by CT-Analyst. There are no time-dependent integrations performed explicitly by CT-Analyst. Instead, all predictions produced by CT-Analyst are simply the result of applying an interpolation procedure utilizing the appropriate nomograph data set based upon the high-resolution CFD results. This same interpolation procedure can be used in both upwind and downwind directions with equal effectiveness. These simple geometric operations are used to determine the probable source zone upwind of each sensor. CT-Analyst provides the capability to immediately backtrack and simultaneously determine the location of multiple unknown sources simply based on sensor readings and meteorological parameters. The plume “predictions” from CT-Analyst, based on a quantitative Figure of Merit, agree, within 80 to 90%, with the FAST3D-CT CFD simulations on which they are based and yet are available much faster than corresponding Gaussian plume estimates (Boris et al., 2002, 2004). Furthermore, the underlying CFD technology is uniformly convergent so answers automatically get better with increasing computer power because higher resolution CFD simulations can be used to build the Dispersion Nomograph data sets (Patnaik et al., 2003).

BRIEF OVERVIEW OF THE WIND TUNNEL EXPERIMENTS

In order to create a high quality reference dataset, which is adequate to fulfill major model- and application-specific validation data requirements for an LES-based, urban flow and dispersion model, numerous flow and concentration measurements were carried out in a extended seven month wind tunnel campaign. A 1:350 scale model of the city center of Hamburg including the harbor area was built for this study. The model covers a total area of 1.4 x 3.7 kilometer. Hamburg was selected as model city in order to analyze dispersion processes in a typical European city. During the first part of the wind tunnel campaign experimental work focused on the characterization of the modeled approach flow condition as well as on flow measurements within the model area (Peeck C., 2011). An extensive set of flow measurements with high temporal and spatial resolution was carried out. Using 2D Laser-Doppler- Anemometry (LDA) delivered component-resolved flow data at sampling rates up to several hundred Hertz under favorable conditions, resolving even small-scale turbulence in time.

During the second part of the wind tunnel campaign the dispersion of clouds of pollutants (puffs) was captured and analyzed by corresponding measurements. In order to characterize the dispersion of puffs properly, large and statistically representative ensembles of puffs were released and the concentration time traces subsequently analyzed. In order to estimate the number of repetitive releases required for achieving a reasonable confidence interval of the ensemble-averaged results a series of pre-tests were carried out. During these pre-tests the scalability of the puff dispersion results was analyzed regarding the released amount of tracer, with respect to the wind speed and in relation to the release duration. During these pre-tests more than 10.000 individual puffs were released. An additional 32.000 puff releases for different source locations and measurement locations within the modeled area of Hamburg were carried out in order to create a comprehensive validation dataset.

WIND TUNNEL FACILITY AND THE HAMBURG MODEL

The wind tunnel measurements were carried out in the large boundary layer wind tunnel ‘WOTAN’. A general drawing of the facility is shown in Figure 1. The 25 m long wind tunnel provides an 18 m long test section equipped with two turn tables and an adjustable ceiling. The cross section of the tunnel measures 4 m in width and 2.75–3.25 m in height depending on the position of the adjustable ceiling.

While in the test section free stream wind speeds of more than 20 m/s can be reached, the typical wind velocities chosen for atmospheric flow and dispersion modeling are in the range of 5–15 m/s. The model boundary layer flow is generated by a carefully optimized combination of turbulence generators (spires) at the inlet of the test section and a floor roughness (Peeck C., 2011).

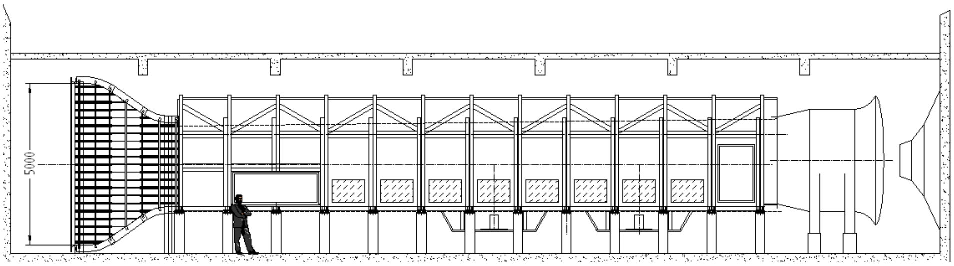

Figure 13. Drawing of the large boundary layer wind tunnel facility ‘WOTAN’ of the University of Hamburg.

Figure 2 shows the Hamburg model mounted in the wind tunnel. The model is 4 meter wide and 10.5 meter long, corresponding to an area of 1.4 x 3.7 kilometer at full scale. For dispersion modeling and measurements several point emission sources were flush-mounted in the model floor. The circular release area had a diameter of 7 mm (model scale), corresponding to 2.1 m at full scale. In order to avoid the formation of a significant vertical jet at higher emission rates, the source area was covered by a lid, 3.5 mm (1.05 m full scale) above the ground level. In order to simulate instantaneous puff releases, a continuous by-pass flow of tracer gas was temporarily switched to the source by means of a fast solenoid micro-valve. With this setup, the release rate could be kept absolutely constant for repetitive releases lasting much less than a second at model scale. The precise repeatability of releases and the consistency of puff modeling were verified by extensive systematic tests prior to the experiments. The puff dispersion was measured by a Fast Flame Ionization Detector mounted to a traverse system. In order to avoid flow disturbances the instrument was located well above the urban structures.

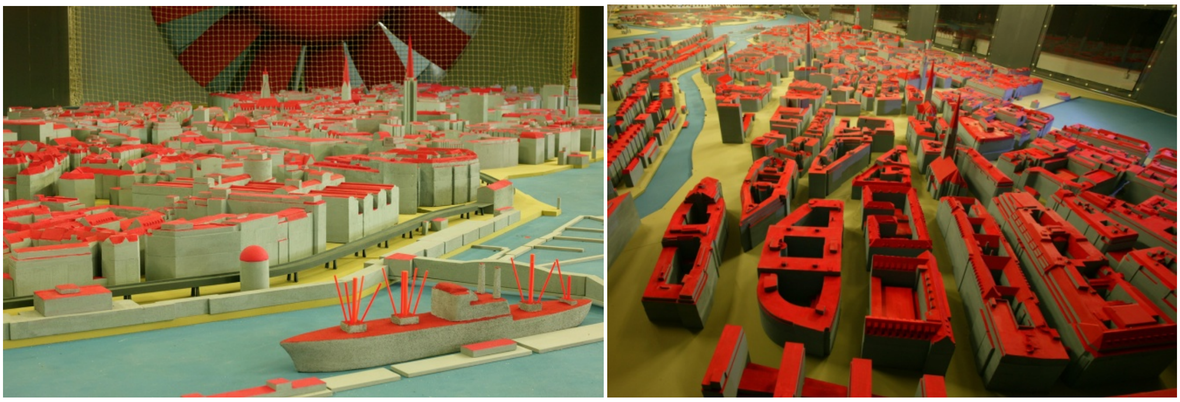

Figure 14. Wind tunnel model of the city center of Hamburg.

BOUNDARY LAYER MODELING

Basic requirement of the wind tunnel measurements was to model a boundary layer flow similar to the conditions found upwind of the city center of Hamburg. In an iterative process the shape and arrangement of the spires and the floor roughness elements were varied until the modeled boundary layer was in reasonable agreement with the full scale conditions measured at a 300 m tall mast located upstream of the city center of Hamburg (Peeck C., 2011). The proper scale of the modeled boundary layer was verified by comparing integral length scales and spectral distributions of the turbulent kinetic energy with those of the real atmosphere. A careful adjustment of the modeled boundary layer enabled even large scale turbulent wind fluctuations up to a time scale of approximately 45 min to be replicated at scale in the wind tunnel.

PUFF DISPERSION MEASUREMENTS

A focus of the project was put on the puff dispersion measurements. One of the specific features of the generated benchmark database is the provision of systematic and statistically representative test data for puff dispersion in urban areas. The large ensembles of individual releases carried out under identical mean wind and release conditions enable a probabilistic approach to be used for the comparison of wind tunnel data with the corresponding CFD results or field data. Comparing individual transient puff signals is not an adequate approach because of the large variation in the shape of time traces. Figure 3 illustrates the variability of individual puff concentration vs. time traces recorded at a measurement location in the wind tunnel for seven identical releases. The instants of releases are indicated by the black bars and the red line states the measured concentration in ppm_v at the measurement location. The figure shows that two of the seven released clouds completely miss the measurement location while the measured concentrations for the other five releases differ significantly. Though the mean boundary conditions were identical for all releases, the observed differences are caused by the turbulent flow field.

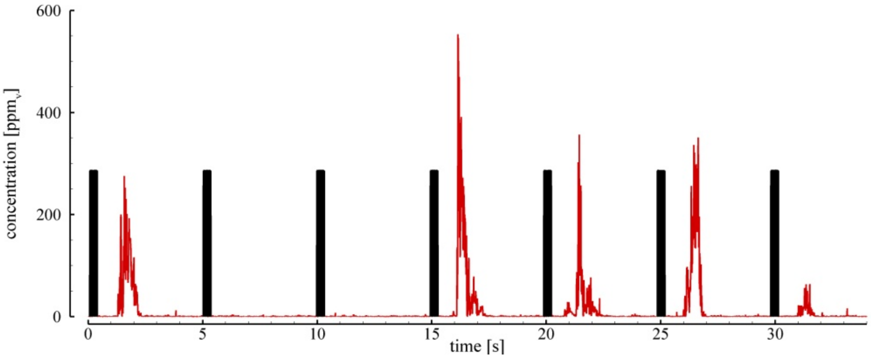

Figure 15. Section of a typical measured concentration signal for seven consecutively released puffs. The release of tracer for each puff is indicated by the black bar.

Although a ‘mean puff’ can be defined from a sufficiently large ensemble of releases, the mean puff is not adequate for comparison with a single release from the field test. A pure pattern-based comparison is far to elaborate for both the wind tunnel data and the CFD results. To simplify the comparison and to enable a quantitative comparison, a puff can be characterized by a number of parameters such as arrival time (at), peak time (pt), leaving time (lt) and dosage (dos) or peak concentration (pc). Each of the parameters illustrated in Figure 4a can be calculated for each of the individual puff signals recorded at a given measurement location. For detecting the arrival time and leaving time from a recorded time series a dosage based method was used. As indicated in Figure 4a the arrival time and leaving time define the time interval after the release when 5% and, respectively, 95% of the total dosage of a puff reached the measurement location.

It was found that the dosage based detection method provides, in contrast to other threshold criteria, a uniform arrival time and leaving time identification for puffs with significantly different concentrations. Furthermore, a puff can be characterized by the duration (lt-at), the ascent time (pt-at), and the descent time (lt-pt).

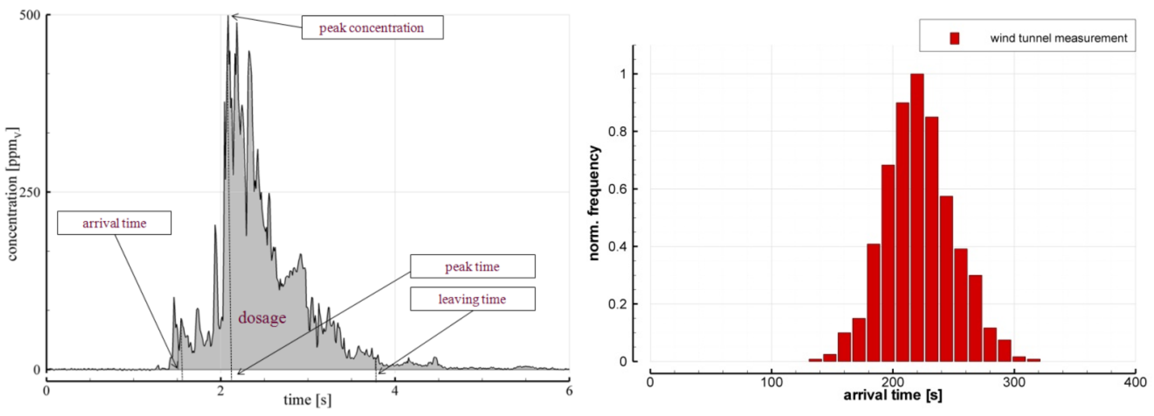

Figure 16. (a) Puff parameters for statistical study. The arrival time is defined as the time after release when the dosage exceeds the threshold of 5%. The leaving time is defined as the time when 95% of the total dosage is reached. (b) Frequency distribution plot for the 'arrival time'-parameter generated by 400 puff releases.

Plotting a sufficiently large ensemble of derived puff parameters, a well-defined and sufficiently smooth frequency distribution can be achieved. Figure 4b shows a frequency distribution plot generated from wind tunnel measurements for the arrival time parameter.

In order to estimate the number of repetitive releases required for achieving a reasonable confidence interval of the ensemble-averaged results, a series of pre-tests were carried out. For a variety of possible measurement locations, several hundreds of individual releases were carried out and ensemble-averaged values of puff dispersion parameters were calculated for gradually increasing ensemble sizes. Additionally for each ensemble size the mean values were calculated by selecting the results of different puff releases. It was found that a minimum of about 200 releases were required in order to reach a confidence interval qualified for model validation while still maintaining a reasonable experimental effort.

Figure 5 shows a typical result of a convergence analysis for the measured puff travel time. In this case 300 identical puffs were released from a source located at a crossing in the city center of Hamburg, modeling a mean wind direction of 235° and a mean wind speed of 2.5 m/s at the height of 80 m above the ground just upstream the city center. The measurement location was located about 400 meters further downstream. The figure illustrates the uncertainty in defining the mean arrival time if the ensemble size is limited.

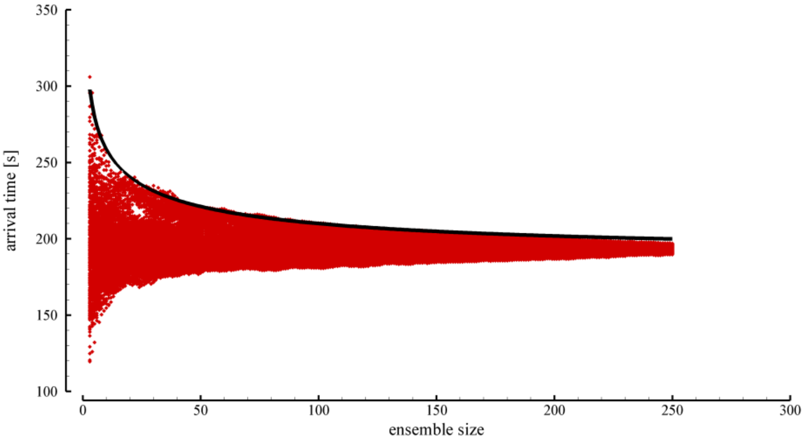

Figure 17. : Mean arrival time calculated for different ensemble sizes.

As expected the uncertainty in defining the mean value decreases with increase in ensemble size. In this particular case 200 releases allow defining the mean arrival time with an uncertainty of ± 5%. This uncertainty increases to at least ± 16% if the mean value is calculated from 50 releases only. For field measurements it has to be considered that due to changing weather the number of puff measurements that can be carried out under similar boundary conditions is typically much less than 50 releases.

As illustrated by the black line in Figure 5 the reduction in the uncertainty with increase in ensemble size can be described by

$$y = A + \frac{B}{\sqrt{n}} \tag{1}$$

where y describes for each ensemble size n the maximum difference to the mean arrival time, which was calculated from all 300 puffs. A and B are the curve parameters whose values may vary depending on the considered dispersion scenario.

The finding is in line with statistical theory according to which the reduction in the uncertainty with increase in ensemble size n is proportional to $1/\sqrt{n}$. The wind tunnel measurements document that the uncertainty in defining mean values depends also on other parameters. For measurements close to the source location the observed concentration gradients are stronger and an increased number of releases are required to define the desired mean values with the same statistical confidence. In addition, it was found that at the same measurement location the uncertainty range differs for various puff parameters. The dosage and peak concentration seem to be the parameters with the largest uncertainty levels. This information is essential when mean values from wind tunnel tests, field experiments, or numerical results are compared with each other.

COMPARISON OF MEASURED AND PREDICTED DANGER ZONES

One objective of the presented study was to validate the predicted danger zones of CT-Analyst. A danger zone marks the area which can be reached by a released tracer for a selected source location and a selected mean wind direction. For this analysis two different source locations and a wind direction of 235° were selected. The tracer was released continuously during the measurements. Figure 6 shows the result of this comparison for the two dispersion scenarios.

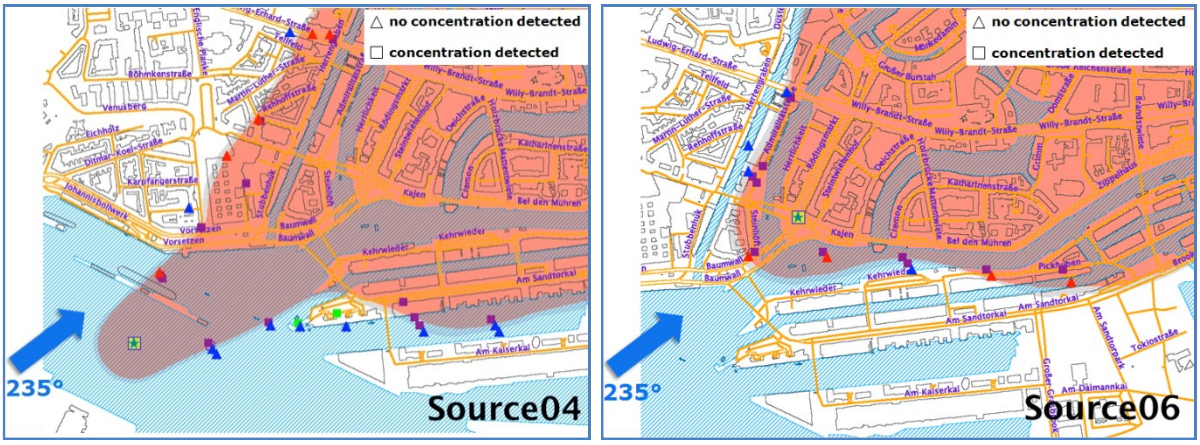

Figure 18. Comparison of the predicted and measured danger zones for two different dispersion scenarios within the city center of Hamburg.

The red area indicates in each case the predicted danger zone by CT-Analyst. The triangles and squares in Figure 6 represent the results of the wind tunnel measurements. A triangle states that no concentration was detected during a 4 minute wind tunnel measurement and a square indicates that within the 4 minute measurement a concentration of 5 ppm_V was exceeded at least once. Hence the area between a triangle and a square marks the edge of the wind tunnel plume. It has to be considered that due to the model scale of 1:350 a 4 minute wind tunnel measurement corresponds to a 24 hour measurement at full scale under identical weather conditions. In order to analyze the effect of the release rate the measurements were repeated for different release rates. It was found that increasing the release rate by a factor of ten has no effect to the detected danger zone. Figure 6 shows that the edge of the plume detected by wind tunnel measurements is in good agreement with the danger zone predicted by CT-Analyst.

CONCLUSIONS

Time-dependent Large Eddy Simulation is a cost effective approach, which has a complexity in between DNS and the RANS methods. Increases in computing power have enabled LES-based modeling to be applied on a routine basis for urban flow and dispersion problems. However, the validation of time-dependent, eddy-resolving LES codes is not as straightforward as it is for models based on RANS methods. A qualitative and quantitative evaluation of an LES code requires statistically valid model- and application-specific test data, and a commonly accepted and scientifically justified validation strategy. Validation procedures become more complex because comparisons must not just be based on mean quantities but on frequency distributions of statistically representative ensembles of results as well. It was found that due to the enormous variability of puff signals, locally measured in an urban environment, a huge number of repetitions of individual releases under identical mean boundary conditions are necessary to estimate the bandwidth of possible results for a particular release configuration. Therefore, validating LES-based numerical models with results from individual puff releases is not meaningful. As shown, carefully controlled wind tunnel measurements provide the possibility to estimate the bandwidth of possible dispersion results even for complex transient dispersion situations. However, sufficiently high experimental standards have to be met in order to ensure credibility of wind tunnel tests and to achieve data qualified for a rigorous validation of eddy-resolving CFD models.

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