ADVANCES AND CHALLENGES IN APPLIED FLOW AND DISPERSION MODELLING

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ABSTRACT
Atmospheric flow and dispersion modelling has been one of the key competences of Wind Engineering for many years. Gradually the variety of tools and methodologies applied in air quality management and control were improved and standards were established jointly by engineers, meteorologists and environmental scientists. However, the recent advances in engineering meteorology, measurement technologies and modelling tools suggest a critical review and possible update of what is accepted to be the state-of-the-art in flow and dispersion modelling in the lower atmospheric boundary layer. The keynote paper outlines some of the actual and future focal points in flow and dispersion modelling within the lower atmospheric boundary layer.

KEYWORDS: LOCAL-SCALE DISPERSION MODELLING, NUMERICAL MODELLING, PHYSICAL MODELING

Introduction

Modelling, predicting and investigating flow and dispersion phenomena in the lower atmospheric boundary layer has been one of the focal points in wind engineering research for several decades. Particularly in the 1970's and early 1980's, numerous contributions to a modern air quality management have been made jointly by engineers, meteorologists and environmental scientists. With the emerging air quality and environmental health problems becoming readily identifiable, standards for protecting human health and to secure the natural environment from degradation by air pollution were developed and politically and practically implemented. The field of Engineering Meteorology was established as a research field covering the interface between Meteorology and Engineering, where meteorological processes interact with engineering objectives. Since then, in the field of applied air pollution control, the principal methodologies for predicting atmospheric dispersion remained nearly unchanged over more than 20 years. The fact that, for example, Gaussian type dispersion models are still widely applied tools for predicting dispersion from elevated sources such as chimneys and cooling towers indicates the substantial work done until the mid 80's. A comprehensive overview of the state-of-the-art by that time is given in Plate (1982).

An increasingly strict environmental legislation lead to measurable and often even visible improvement of air quality in many industrialized countries. Not only the increased availability of cleaning technology for exhaust gas from industrial sources but also the availability of prognostic tools for local scale dispersion problems enabled the qualitative and quantitative enforcement of environmental laws by a gradual decrease of limit values defined for most of the pollutants. In the 1990's, the regulatory requirements started to change because the remaining observed air quality and dispersion problems could no longer be attributed to local emissions from large industrial sources alone. Improved air quality
monitoring revealed that particularly in urban areas most of the air quality and pollutant dispersions problems are resulting from distributed sources such as road traffic, characterized by a significant spatial and temporal variability (Sokhi and Bartzis, 2001). Environmental policy usually is 'adapted' to the new quality of the problem by cutting the evaluation time period for characteristic pollutant concentrations from, for example, an annual mean value down to an hourly maximum value not to be exceeded within one year. What - at least seemingly - does not change the strategy of monitoring air quality by local measurements, is causing profound consequences with respect to air pollution modelling at local scales. Whereas dispersion modelling in past mainly dealt with mean flow and dispersion problems, the current challenges are in the field of predicting the transient dispersion phenomena in heterogeneous environments. In this context, improved monitoring and modelling strategies have to be developed and established in order to predict dispersion in complex geometries during short-term immission scenarios. The strategies for defining proper boundary conditions applicable to local-scale flow and dispersion modelling as well as the modelling approaches need to be revised carefully in order to handle the more complex dispersion problems adequately.

**Boundary Conditions**

As any other diffusion problem, the dispersion of pollutants in complex urban geometries is dominated by the actual physical and geometric boundary conditions. The latter is less difficult to be characterized for urban environments due to the increasing availability of sufficiently accurate information on the urban building structure in digital information systems such as GIS. However, the available geometric information must be replicated in a model environment properly - either in a numerical model or in a wind tunnel model setup - in order to maintain sufficient geometric similarity. In this context, the term 'sufficient' has to be defined carefully, depending on the problem to be simulated. Flow and dispersion modelling, for example, within the urban canopy of a typical European city requires the majority of slanted roofs to be replicated in the model adequately in order to maintain similar flow conditions at roof level. Figure 1 provides an example of the simplifications applied in this regard by showing a typical wind tunnel model of an urban area (left) as well as its numerical counterpart (right) as used for local-scale urban air quality modelling (Leitl et al. 2001). The use of unstructured grids for numerical simulations is expected to solve the problem at the cost of a substantially higher computational effort.

![Figure 1: Simplification on urban structures as tested in a wind tunnel.](image-url)
Already more problematic is an adequate characterization of the physical boundary conditions as, for example, the wind conditions driving the dispersion process within a short evaluation time period such as one hour. Whereas in a conventional modelling approach, a mean wind profile can be defined, 'just one' representative mean wind profile does not exist for relevant time periods of up to a few hours of identical mean wind conditions. The presence of turbulent structures in the lower atmospheric boundary layer and the continuously changing meteorological conditions inhibit the forming of a statistically representative 'mean' wind profile. As documented by numerous field data sets, the shape of an hourly averaged 'wind profile' can scatter significantly, even if the 'mean approach flow conditions' are identical. Consequently, mean approach flow conditions have to be understood as ensemble average over finite ensembles of data with a more or less big scatter of individual wind data around the corresponding mean value. Only if the mean profile as well as the underlying inherent fluctuations of the approach flow conditions are properly derived from field data and carefully replicated and documented in a model experiment, the similarity between model simulations and full-scale conditions can be assumed to be sufficient for translating model results to full-scale conditions or for comparing simulation results directly with corresponding field data. It requires spatiotemporal analysis tools such as correlations, proper orthogonal decompositions (POD) or linear stochastic estimations (LSE) to be applied for characterizing wind flow boundary conditions adequately. Evaluating only the mean wind profile is not sufficient when simulating and analyzing transient flow and dispersion phenomena developing during time periods up to several hours at full scale. Particularly for the validation and use of eddy-resolving numerical flow and dispersion models, this information is vitally important in order to ensure the proper spatiotemporal fluctuations of wind vectors to be replicated at the inflow boundary of a model domain. In this regard, a substantially better characterization of inflow data can be provided based on dedicated boundary layer wind tunnel tests. Once physically consistent and representative mean flow conditions can be documented for a wind tunnel setup, sufficiently long wind velocity time series can be recorded. For an atmospheric boundary layer flow modelled in wind tunnel, time series of several minutes must be recorded in order to achieve a sufficient statistical representativeness of the inflow data, when then natural variability of winds is replicated properly. The several minutes at wind tunnel scale correspond to at least several tens of hours at full scale, indicating the general restriction of field data to provide representative mean wind conditions from time limited measurement campaigns. However, the sufficiently long tunnel time series can be divided in sub-samples corresponding to full-scale time periods of, for example, 30 minutes or one hour and the expected variability inherently present in field data can be estimated and systematically analyzed. Even if the wind tunnel model is just a model result as well, it enables the minimum expected variability of short-term averaged field data to be characterized and quantified. In addition, this type of data analysis is expected to substantially foster the provision of physically consistent inflow boundary conditions for eddy-resolving numerical models such as LES. Figure 2 shows an example of corresponding wind profile measurements acquired for an urban type boundary layer flow, modelled in a wind tunnel. The red symbols document the related statistically representative mean wind profile with the experimental repeatability of the long-term average value being indicated by the scatter bars. A rather large data ensemble is represented by the light grey symbols, corresponding to approximately 2.5 hours of averaging time at full-scale. The dark grey symbols represent profiles measured within just one 15 minute time slot at full-scale.
Even the more simple strategy of characterizing approach flow conditions based on a stationary wind profile requires, for example, sufficient knowledge about the actual boundary layer thickness in order to evaluate the wind flow conditions to be 'representative' for relatively short periods in time such as one hour. In practical applications, the problem of defining a 'proper' shape for a short-term mean wind profile is often shifted to the definition of a corresponding roughness length. Formally, the roughness length approach is tying the wind profile to a parameter expected to be independent from the driving meteorological conditions and the desired 'evaluation time period', as long as $z_0$ is seen as a pure morphometric parameter. However, when a roughness length approach is applied to an urban area, both, the local heterogeneity of the urban roughness as well as the effective radius of a local aerodynamic roughness changing with wind speed is causing a variety of plausible $z_0$ values to be 'representative' for a short evaluation period. Figure 3 shows results for a 'typical' European urban roughness being modelled in a wind tunnel facility. Within the scope of the Basal Urban Boundary Layer Experiment BUBBLE, the local heterogeneity of wind and turbulence data was documented by corresponding wind tunnel measurements by Feddersen et al. (2003). As documented by the corresponding wind profile measurements, the lower part of the wind profile quickly adapts to local roughness changes, causing the related roughness length parameter to scatter dramatically within a range of a few hundred meters. The behaviour is documenting clearly that, from a physical point of view, the roughness length concept is not a proper approach to characterize wind conditions above a heterogonous urban roughness. An even higher local variability was observed in the corresponding turbulence data such as turbulent momentum fluxes.

It becomes clear, that defining boundary conditions relevant for short-term dispersion processes is a non-trivial task. Averaging the expected variability inherent in short-term boundary conditions as it is done for the use of conventional diffusion formulæ is obviously not a proper approach because it can blur or even ruin the quality of dispersion modelling results, no matter how good or bad, the actual model is.
Figure 3: Spatial variability of mean wind profiles above an heterogeneous urban roughness.

Needed in the future are strategies for defining model- and application-specific boundary conditions which are physically justified at relevant time scales. In the context of representative wind profiles, at least statistically characterized ensembles of representative wind profiles are required to characterize the variability of the inflow boundary conditions. However, due to the limited spatial and temporal resolution, such data cannot be obtained with sufficient accuracy from field measurements only. A feasible approach can be the combination of representative 'mean' field data with corresponding results from a validated, eddy-resolving flow model.

In this context, another fundamental problem arises when ensemble-averaged field data have to be compared or combined with corresponding model results from a wind tunnel model or CFD simulation for example. For scaling, harmonizing and properly comparing or combining inflow boundary conditions and model results, a representative reference wind measurement is required. Whereas spatial and temporal representative reference data can be educed with reasonable effort for model data, the equivalent field data are almost impossible to be acquired during field measurement campaigns. Due to the spatial and temporal variation of locally measured winds documented above, reference values are expected to vary significantly, depending on where and when the measurement was taken and what the averaging time period was applied.

**Complex Flow and Dispersion Modelling**

Numerical flow and dispersion modelling was subjected to significant improvements within the last decade. With the rapid increase in computing power, more complex numerical models are applied to atmospheric flow and dispersion problems on a routinely basis. The most obvious improvement in this regard is perhaps that models can resolve individual obstacles in complex geometries with sufficient detail but the advances in modelling turbulent flow phenomena within the lower atmospheric boundary layer are of even bigger relevance.
With modern CFD models flow and dispersion scenarios can be simulated for quasi-stationary as well as transient situations, depending on choosing a RANS- or LES-based model approach. Assuming that the required model- and problem-specific boundary conditions for a simulation could be provided with sufficient accuracy, the validation of complex transport and diffusion models remains a very big challenge. While conventional 'mean dispersion models' could be tested reasonably well on a finite number of field or laboratory data sets, the more complex models and application scenarios require a much bigger effort in proving the physical validity of the results. Despite the limitations physical modelling in boundary layer wind tunnels has from a meteorological perspective, wind tunnel tests are one accepted source of validation data for numerical flow and dispersion models.

In this context, activities such as the recently accomplished COST 732 Action are intended to provide guidance in the process of validating advanced models. Based on a structured set of quality measures to be applied to well-defined test simulations it is not intended to rate the models but to quantify their specific performance measures for urban-like flow and dispersion scenarios. The validation strategy outlined by COST 732 seems to be applicable at least to RANS-based codes (Franke et.al. (2008)). With the next generation of advanced LES-based flow and dispersion models already being used in a practical context, the existing validation strategies need to be extended and particularized for LES-codes as well. Here, the specific strength of time-dependent, turbulence-resolving model results perhaps becomes the biggest problem for adequately validating such codes. In most cases, running an LES-code for generating mean flow and dispersion fields would be far too laborious. On the other hand, replicating individual short-term flow and dispersion events will not provide the basis for a comprehensive validation similar to what has been outlined in COST 732. Besides defining model-specific performance measures, a big challenge will be the provision of data qualified for model testing. A possible way of validating the results from an LES-based urban puff dispersion simulation is outlined by Lee et.al. (2009). By combining results from individual field trials with statistically representative ensemble data of systematic puff dispersion experiments carried out in a boundary layer wind tunnel facility, the reference data for testing an LES-based transport and diffusion model could be provided.

Using boundary layer wind tunnel modelling as - not the only, but one additional - valuable source of information and data requires the existing physical modelling standards to be reviewed critically as well. Most of the experiments documented in literature still illustrate the boundary layer wind tunnel modelling standards established in the 1970's and 1980's. Modelling approaches and simplifications still feasible when investigating wind loads on structures are not sufficiently strict when turbulent flow and dispersion phenomena are in focus of wind tunnel experiments. Whereas significant load effects often can be attributed to distinct classes of turbulent eddy sizes, dispersion involves all turbulent scales present in the lower atmosphere and turbulent flow structures have to be modelled and documented carefully to ensure similarity with full scale conditions. As in numerical modelling the increase in computing power has lead to advanced numerical modelling concepts, the availability of advanced measurement techniques enabled the quality of boundary layer modelling in wind tunnels to be improved significantly. By replicating complex full-scale conditions sufficiently accurate on one hand and providing complete sets of test data on the other hand, physical modelling can help to bridge the gap between full-scale data and numerical modelling in the context of model validation.

Conclusions

The focus of transport and diffusion modelling in the lower atmospheric boundary layer has been shifted from long-term mean values of pollutant concentrations to predicting flow and dispersion patterns for short evaluation periods. Particularly in urban environments,
conventional dispersion modelling is replaced by advanced flow and dispersion models capable of resolving the complexity of flow and dispersion patterns. The progress in dispersion modelling is not yet facilitated by a corresponding improvement of the input information needed for model runs and the provision of reference data for testing the more complex tools currently emerging. It is one of the challenges of Wind Engineering and Meteorology to review, partly readjust and improve the knowledge on transient flow and dispersion phenomena in the lower atmospheric boundary layer according to the needs of current environmental policy.

References


