Methods of investigating urban wind fields—physical models
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Abstract

For evaluation of environmental problems in urban areas, models are needed. Physical models and mathematical models are the tools of the trade. Both types of models have advantages and limitations. The emphasis here is on boundary layer wind tunnels, which are well suited for the study of many urban climate situations. The boundary layer flow along the floor of a meteorological wind tunnel is a real flow which approximately represents a scaled down version of the atmospheric boundary layer under conditions of neutral stratification. Therefore, important practical problems involving urban atmospheric conditions can be studied in such wind tunnels by means of geometrically similar models of the urban area. Such problems involve wind forces on structures, pedestrian comfort, and diffusion processes from point sources, such as chimneys, tunnel exhausts and gaseous spills, or from line sources, such as traffic lines. The investigation of these processes in a wind tunnel must be seen, however, as one link only in a chain of actions. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

For the purpose of deciding on environmental improvements urban planners require two types of analyses: the analysis of existing situations, and the analysis of planned developments. For the former type of analyses, field studies are the best way of obtaining information. However, because of the high cost of lengthy field studies, it is usually not possible to study the full range of meteorological conditions for the site. City planners are asking for models, by means of which they can study the existing situation in detail without extensive field measurements. Models are even more important for studying the second type of planning situations: those of future developments, for which field studies are not possible. Field studies therefore are not the best answer for planning. They should mainly be used as a means of monitoring the environment, or, in the context of planning for the future, for providing information for setting initial conditions, or for model calibration or verification.

In order to assess the effect of urban developments on urban conditions, modelling is necessary. Models allow to investigate future conditions, and to compare them with an existing situation. Typical questions for which answers are needed are:

- How do existing buildings influence the wind forces and wind pressures on new buildings, or how do new buildings affect forces and pressures on existing buildings?
- How will the wind field in an existing urban area be affected by a new building, or by whole new housing developments? Will the pedestrians be affected by strong local winds and wind gradients?
- What will be the immision of NOx caused by traffic if a new street or highway is being constructed, or if traffic or other line sources are changing?
- How will an automobile tunnel affect the exhaust load in the area around the tunnel outlet, or how will industrial point sources affect the air quality in urban areas?

Such questions require answers, which can only be given by means of physical or mathematical models. Both types of models have reached a stage where routine application is possible, within the limitations of the different methods (see for example the extensive discussions and examples in the papers in Cermak et al., 1995). Depending on the type of task to be performed, one may distinguish three different categories of models.

The first category consists of screening models: simple models which capture the essentials of a situation and
which permit to assess the upper limit of a potential load, which could be a critical pressure, or force, or wind speed, or concentration. For example, if the wind load is only a minor factor in the total load on a building, then the use of code values is quite sufficient, because a more accurate determination of the wind forces would not change much in a design. If wind is important, then screening models can serve to evaluate preliminary designs, before the decision is made to study the final design in a wind tunnel. Similarly, if one finds that the concentrations, if evaluated by a screening model, are far below critical concentrations, then no need exists to go into more detail. For forces and pressures, the use of codes, such as the German standard DIN 1055 Pt. 5 may be classified as belonging into this category. Screening models for pollution loads have been developed on the basis of parameter studies in wind tunnels, which are either used directly – for a collection of such models see for example, Meroney (1982) – or as part of diagnostic mathematical models. However, screening models have to be carefully tested, and it can be dangerous to apply screening models to situations deviating much from those cases for which they have been verified.

The second category of models are models where details are required, either because results obtained from screening models are near or above critical, or because local maxima are to be found — such as pressures on the cladding of buildings, or concentrations in the source region or the near field of a pollutant source. In this category, wind tunnels find their most useful application.

The third category of models is for investigating large-scale environmental effects caused by superposition of many sources, such as generated by traffic, into a coherent and distributed model, based on Geographical Information Systems and integrated representation of urban characteristics ranging from effects of topography to models of cold air movements (see for example the case studies presented at the ICUC96 conference). In this category, details are not required, and numerical models can handle such complex situations.

2. The nature of models: possibilities and limitations

Models are either physical models, analytical models, or numerical models. Physical models are models in which the urban situation to be studied is reproduced at a small scale. Typical experimental devices are wind or water tunnels, flow tables and other devices, in which the atmospheric flows are modelled with real fluids and small scale replicas of the actual buildings or actual topographies. Most developed is the modelling technology for neutrally stratified atmospheric flows, for which boundary layer wind tunnels are used.

Both analytical and numerical models are based on mathematical abstractions of the fluid dynamical processes. Analytical models yield closed solutions of the basic equations describing the process. Only a very small number of analytical models exists for urban processes, most prominently Gaussian plume models as solution of the linear diffusion equation for simple boundary conditions. Numerical models usually make use of a numerical grid for the flow field along a (usually flat) boundary, into which simple geometric shapes representing the buildings and their arrangement are placed, then replace the basic partial differential equations of fluid mechanics with finite difference equations, which are solved at the nodes of the grid by means of a digital computer.

Except for very low Reynolds number flows and simple boundary conditions, numerical models have the shortcomings to be based on simplifications of the governing equations and of the initial and boundary conditions. This is required by the structure of the governing equations of fluid mechanics, the highly non-linear Navier–Stokes equations, which have the unpleasant property of becoming unstable and leading to turbulence for all but the smallest Reynolds numbers. The planner or his consultant can draw from a rich offer of approximate numerical models which have been developed over the last decade. Among them are the Regional Atmospheric Modelling System (RAMS), a mesoscale atmospheric model, which has been adapted by Nicholls et al. (1995) to applications within urban areas, and turbulence models based on an empirical closure of the turbulent energy equation (κ-ε models, Rodi, 1984). Newer models, based on separating the flow field into components of different eddy sizes, are large eddy simulation (LES) models, Murakami et al., 1992), which are, however, not yet available for standard applications.

If properly calibrated, many numerical models can serve very well for modelling overall features of flow fields. However, for details of the turbulence field and for complex geometrical features, such as details of topography, building complexes, or building forms, etc., they have not yet been validated to a sufficient extent. If such details need be investigated, then the boundary layer wind tunnel is, at this time, the only reliable “analog computer”. This is due to the fact that the boundaries can be modelled with all necessary details, and the flow field in the wind tunnel is a real flow field. Therefore, the Navier–Stokes equations are exactly satisfied. The only question is whether the flow field in the wind tunnel is indeed a scaled model of the flow field of the atmosphere. The answer to this question depends on the application of the study. Many comparisons of field and wind tunnel investigations have shown that modelling is very accurate for forces and pressures on buildings, which depend on mean flow and that part of the turbulence, whose eddies have dimensions of the same order as building dimensions, and these are modelled very well in a wind tunnel (Plate, 1982). Because wind forces are the highest at highest wind velocities, wind tunnel studies can be...
done with high wind velocities. This has the advantage of giving high Reynolds numbers – a requirement for modelling – and of giving large signals, which can be measured comparatively easily. On the other hand, modelling of concentration fields, such as caused by the continuous release of pollutant gas from a chimney, is possible only within certain limits, because in a wind tunnel one can neither reproduce the large-scale eddies, which are generated by mesoscale meteorological processes, nor Coriolis forces, so that the veering of the wind after some distance is not modelled well. Furthermore, for the same situation, concentrations are higher at low wind velocities, and with decreasing wind speeds stratification effects become increasingly important.

For diffusion investigations it is useful to distinguish four regions of applications of different modelling techniques, which are shown schematically in Fig. 1:

1. An initial region, extending over a few tens of meters, involving the building under consideration or its direct surroundings, which can only be modelled in a wind tunnel.

2. A near field region, extending up to a few hundred meters, in which the exact location of the source is not important, because the buildings downstream of the source strongly influence the wind field and cause strong mixing, which obscures the initial conditions. The outer edge of this region is formed by the “radius of homogenisation”, which obtains its name because beyond this distance the concentration plume can be modelled as if it were in a field of homogeneous turbulence.

3. A far field region, extending over maximum of up to 4–5 km, of interest mainly for long-range air pollution studies, where simple models of the Gaussian plume type can be used to calculate concentration fields from urban sources. However, these Gaussian plume models require initial conditions determined by the characteristics of the urban area, as was shown by Theurer et al. (1996), and they usually lead to conservative estimates of maximum concentrations, because the spreading effect of the largest scale turbulence cannot be included in wind tunnel studies.

4. A fourth region, influenced by mesoscale meteorological processes and Coriolis forces, where the gaseous releases from all sources can be superimposed by means of mesoscale atmospheric transport models (for example, Adrian and Fiedler, 1991).

3. Wind tunnel modelling

Extensive literature exists on the methods for modelling atmospheric boundary layers in boundary layer wind tunnels (Cermak, 1972; Plate, 1982). The most important modelling requirement is the establishment of a nature-like boundary layer along the wind tunnel floor, as is indicated in Fig. 2. This is obtained by having the wind velocity distribution \( u(z) \) develop along a uniformly rough floor of a boundary layer wind tunnel. To reduce the effective length of the test section, the velocity profile is reshaped by means of turbulence generators and large floor roughnesses. Into this fully developed boundary layer (corresponding to an average suburban boundary layer), the scale model of the city complex to be studied and its surroundings is placed. The surrounding part ahead of the study area forms a development distance (determined by the internal boundary layer along the city, about 10 times the thickness of the boundary layer, see Garratt, 1990), after which the boundary layer corresponds to the scaled down atmospheric condition. It consists of four sublayers, schematically indicated in Fig. 2. The lowest layer is the canopy layer. It is the flow layer between the buildings, in which the buildings themselves determine the local flow field, and its height is of the order of the average building height \( h \). In the canopy the
flow is determined by the drag on buildings and surface elements. The mean velocity profile in the free spaces between buildings decreases gradually with decreasing height \( z \). The flow is highly turbulent and three-dimensional. Above the canopy there exists a blending region of thickness \( d \), of order \( 2d_0 \), in which the velocity profile changes from the canopy profile to a logarithmic shape. In this blending region, the mean velocity becomes progressively more two-dimensional with height, and drag-induced pressure gradients are gradually converted into a horizontal shear stress \( \tau = \rho \cdot u_w^2 \), which then remains approximately constant with height, up to a height of about \( 0.15d \), the wind profile obtains a logarithmic and is scaled according to the law

\[
\frac{u(z)}{u_w} = \frac{1}{\kappa} \ln \left( \frac{z - d_0}{z_0} \right) \quad \text{for} \quad z > 2d_0
\]  

(1)

In this equation, \( u_w \) is the mean velocity, \( \tau_0 = \sqrt{\tau_0/\rho} \) is the shear velocity, with \( \tau_0 \) the shear stress exerted by the wind on the ground, and \( \rho \) is the density of the air. Furthermore, \( d_0 \) is the zero plane displacement, a length which is approximately equal to the thickness of the canopy layer shown in the definition sketch (Fig. 2), and \( \kappa \) is the von Karman constant, equal to about 0.4. The length \( z_0 \) is a measure of the roughness of the surface, and is a specific quantity for each type of urban development, as shown, for example, by Wieringa (1992) or Theurer (1994).

Proper modelling of the atmospheric surface layer requires that the ratio \( z_{om}/z_0 \) is equal to the geometric scale ratio. In this ratio, the index \( n \) refers to natural conditions, and index \( m \) stands for the model. Geometrical similarity is sufficient to generate a flow which is correctly scaled, provided that the atmospheric stratification is neutral or near neutral, that all buildings are approximately sharp-edged, and provided that the Reynolds number \( Re = \frac{uH}{v} \) is larger than 5000–10,000 – a value which ensures that the flow field is not changing with velocity.

The logarithmic law is valid in the constant shear stress region, which is a layer near, but not too near the ground, as indicated in Fig. 2. For the whole of the boundary layer, and particularly for the outer layer, it is common practice to describe the wind by a power law

\[
\frac{u(z)}{u_{ref}} = \left( \frac{z - d_{op}}{z_{ref} - d_{op}} \right)^{\alpha}.
\]  

(2)

Modelling requires that the exponent \( \alpha \) must be the same in model and in nature – which implies similarity of shape of the velocity profiles. The displacement height \( d_{op} \) for the power law is not the same as that for the logarithmic law, and has to be determined from the model tests. For the initial conditions upstream of the test area, the assumption \( d_{op} = 0 \) is quite adequate.

For studies involving urban areas the usual practice is to model on a scale of 1 : 100 to 1 : 1000 the part of the city of interest and its surroundings, and to select a velocity profile according to Eq. (2) as initial condition for the velocity reaching the modelled area. The basic profile is that of the flow in suburban areas – most of the time taken to correspond to a value of \( \alpha \) of about 0.23. As mentioned before, the model of the city complex has to be sufficiently detailed over some distance upstream of the region to be studied, so that the effects of the surrounding buildings are correctly included. However, the modelling of the mean velocity field only is not sufficient. The turbulence structure also has to be modelled adequately, which in the case of urban flows implies that separation eddies must form on the edges of roofs and other building surfaces. This is accomplished by using large enough
Reynolds numbers, and by sharpening the corners of all buildings in the model, as was mentioned above. In this manner, the high-energy range of the turbulence energy spectrum of the approach flow is scaled correctly. However, for studies of small-scale turbulence effects, such as fluctuating pressures at points this may not be sufficient. Recently, it was also stated that the small-scale turbulence must be scaled as well (Tieleman et al., 1997). The validity of this approach for obtaining mean pressures, etc., has been verified by comparisons of results from wind tunnel experiments with natural conditions (see, for example, Bächlin et al., 1991).

For traffic pollution studies detailed considerations have to be given to modelling of the turbulence induced by moving vehicles. We have simulated moving traffic by means of a moving belt with small rectangular plates, which generate a scaled amount of turbulent energy of the appropriate eddy size, according to modelling criteria suggested by Plate (198); see also Pearce and Baker, 1997).

Wind tunnel modelling is generally restricted to neutrally stratified flow. Recently however, wind tunnels have been designed which are capable of also modelling the flow in the mixed layer underneath an elevated inversion (see Rau et al., 1991). It has been shown by Fedorovich et al. (1996) that the wind tunnel of Rau et al. (1991) yields a velocity field, which in its mean flow and turbulence characteristics, as well as its thermal properties corresponds very well to results obtained either in the atmosphere or by means of large eddy simulations, so that it can be used with confidence for modelling urban situations.

4. Examples of wind tunnel applications to urban planning

In building aerodynamics for urban areas one distinguishes three typical applications, wind force determinations, pedestrian comfort studies, and diffusion studies. The first concerns wind forces especially in urban environments. At present, wind load codes of most countries contain coefficients for forces and pressures which are obtained in aeronautical wind tunnels. The experiments for their determination were done on buildings which were standing free, that is without buildings in their surroundings, in a wind flow generated along the smooth bottom of classical aeronautical wind tunnels. These conditions neither correspond to the naturally occurring boundary layer flow – which is the flow along a rough boundary, as discussed above – nor do they reflect the influence of the surroundings. In general, due to these neglected conditions, the forces and pressures do not correspond very well to reality; mean force coefficients and pressures generally are lower, but the turbulent components of the pressures are higher than that observed in nature. Only experiments in boundary layer wind tunnels can provide realistic coefficients for these quantities.

In such experiments, pressures are measured with pressure transducers which have been connected to tiny piezometer holes in the model surface through flexible tubing. The transducers yield voltages proportional to the fluctuating pressures. Their analysis leads to the dimensionless pressure coefficient \( c_p \) for the local pressure:

\[
    c_p = \frac{P_{\text{m}}}{\frac{1}{2} \rho u_{\text{ref}}^2}
\]

which depends on the location and on the selected reference velocity (for example, \( u_{\text{ref}} = u(h) \) at \( z = h \)). Index \( m \) refers to the model situation. If modelling has been done correctly, then \( c_{pm} = c_{p\text{me}} \) where the index \( n \) stands for nature, i.e. the (mean) pressure coefficient is assumed to be invariant both under geometric scaling and under changes of velocity.

Of special significance are pressure distributions near the edges of the building, where large pressure fluctuations are generated by separating eddies. These can lead to instantaneously strong pressure peaks, which may cause failure of the cladding material, such as glass panels, or which in the long run may lead to fatigue failure of the fasteners for the cladding elements. The most distinguished eddy is the double-cone-shaped eddy structure which is generated on a roof if the angle of attack of the wind is under 45° to the normal on the front.

As an example of a wind tunnel investigation of forces and pressures, the case of the two towers of the World Trade Centre in New York is shown in Fig. 3. This is from a classic study in which Cermak and Davenport were the first to use the principle of aeroelastic testing developed by Scruton (1963) to obtain data for design of high rise buildings. The effect of local turbulence induced by the high building environment of New York city, as well as the wake interference of the two towers and their effects on street level winds has been studied. Separation from the buildings in front causes eddies which induce strongly fluctuating local turbulent pressures, which can be of significant influence on the local loads on claddings and roof coverings.

Pedestrian comfort is studied by identifying local high winds induced by the geometry of the buildings. A frequently used method for identifying these areas is sand erosion: the floor of the tunnel, corresponding to the street level of the urban area, is a black panel for the urban area model. The model buildings are fastened to this panel, and the floor between the model buildings is covered with fine white sand. Then the wind flow in the wind tunnel is started, and the wind speed is increased in steps, thereby increasing the shear stress on the floor. When the local wind speed exceeds the critical shear stress for sand movement, the sand is blown away, revealing the black floor panel, and thus indicating high wind areas. Multiple exposures show black areas where erosion occurred at the lowest wind speed, the darkest grey
corresponds to the area eroded at the second lowest speed, etc. An example is shown in Fig. 4, from a study done in a wind tunnel of the writer. Such results give valuable clues indicating critical areas, but they should not be used for quantitative conclusions (Livesey et al., 1990).

The most important contribution of wind tunnel studies to urban planning is in the field of pollution from different sources, caused for example by line sources of moving traffic in street canyons of different configurations, or by point sources of different origins, like exhaust vents from garages or kitchens, or from the chimneys and ventilation of factories. If the quantity to be determined is a concentration, then the wind tunnel experiment is conducted with an emission $E_m$ which yields the dimensionless concentrations $c^*(x, u_{ref})$:

$$c^*(x, u_{ref}) = \frac{c_m(x, u_{ref})}{E_m} u_{ref} h_{m}^2.$$  \hspace{1cm} (4)

The measured concentration is $c_m(x, u_{ref})$, the reference veloc for the model is $u_{ref}$, and $h_{m}$ is a characteristic length. The model emission $E_m$ has the dimension $c_0 Q$, where $c_0$ is the concentration in the emitted gas flow rate $Q$, which is selected to yield concentrations $c_m$ in the model, which can be measured conveniently with suitable analysis equipment.

Fig. 5 shows a typical example of a study done in a wind tunnel of the writer for the centre of the city of Stuttgart, where a new city tunnel was planned as an extended underpass under a major traffic artery. The exhaust from the tunnel is mixing with the background pollutant concentrations, and unless the tunnel is specially ventilated, there will be a heavy pollution load on the newly planned buildings (dark buildings in Fig. 5). For the study, a line source was developed, discharging a continuous stream of tracer gas, at a constant rate, which is mixed by the turbulence with the atmospheric air. The diffusion of the gases is strongly modified by the buildings as well as by the traffic, the latter being modelled by means of a moving belt, on which small plates are mounted whose drag causes a traffic-like turbulence. The concentration of the tracer gas is measured at a number of critical points, and for each of the important wind directions.

### 5. The action chain for urban micro-climate assessment involving wind tunnels

The examples shown are typical cases out of numerous studies which are done in many parts of the world. However, a boundary layer wind tunnel evaluation of pressure and force distributions on buildings in urban areas, or of concentration fields for emissions from point or distributed sources can only be done for given external conditions. The natural variability of climates, in urban areas or elsewhere, imposes a severe restriction on the value of the results obtained from model studies, and in the planning of new buildings it therefore is best to
evaluate their effects by studying relative changes – by comparing critical situations without and with the planned modification. This method is frequently applied. However, it does not give an indication of the likelihood of the critical situation to occur. Also, in some applications, a single realisation of the wind field is not of interest, but the cumulative effect of the wind meteorology over the year.
For such studies, it is necessary to consider the natural variability of the factors governing the problem, and to integrate the wind tunnel study into a chain of processes. Each situation of urban wind field has a weight which is governed by the frequency of its occurrence. Therefore, the effect of this situation on the desired decision criterion has to be weighted by considering the cumulative effect of each link of the action chain shown in Fig. 6, each of which requires its own model and database, and each of which introduces its own source of uncertainties and variability.

The first link of the chain is the quantification of the meteorological situation. It is described by the wind profile for the suburban area (as a function of wind direction, if required), and by the two-dimensional frequency distribution of wind velocity and wind direction, as determined at a reference station. For this, meteorologists are challenged not only to provide the data from the nearest weather station, but also to critically evaluate their quality, because the long-term time series of wind velocities are often non-stationary due to changes in the direct surroundings of the weather stations. Also, the wind information obtained from a wind mast must be converted into a wind profile, if possible for each wind direction, and into turbulence parameters, such as intensity and spectra, so that the reference conditions are obtained for an undisturbed height (for example \( u_{ref} \) usually at 10 m) above the surroundings, which can be transferred to the wind tunnel. The result is a series of initial conditions of wind profile, of \( u_0 \) and \( z_0 \), to be used as input for wind tunnel or numerical investigations.

The second link of the chain consists of the conversion of the reference wind field into the wind field at the location which is to be investigated. At this site, both mean and turbulent velocities must be properly modelled, which in wind tunnel technology requires that the surroundings of the building complex to be investigated must be incorporated into the model. The result is the local wind field into which the building or the source is to be embedded. It yields the local reference velocity (for example, \( u_{ref} \) at the scaled building height \( H \), for example \( H = 10 \text{ m} \)). In some cases, this conversion is done by means of wind tunnel studies, but more common is to erect a wind measuring station near the site and to establish a correlation, over some time between the reference station of link 1 and the local station.

The third link consists of the conversion of the local reference wind field into the quantity of interest, such as forces or stresses in the case of force determination, or local wind velocities for pedestrian comfort studies, or concentration fields for air pollution studies. This conversion is produced by the aerodynamic transformation, described by means of the aerodynamic admittance.

The fourth link describes the conversion of the results from the wind tunnel (or a numerical model) into the reaction quantities of the full-scale case. The result of the forces and pressures are internal stresses or deflections, calculated by means of the methods of mechanics. This conversion of external to internal quantities is described by the term structural admittance. For pollution studies this link simply consists of converting the dimensionless quantity \( e^* (z, u_{ref}) \) into prototype concentrations by multiplication with the factor \( E_n/\mu_{ref} \).

The fifth link stands for the evaluation process where the calculated prototype quantities are compared with permissible values. For structural design, stresses or deflections are compared with admissible stresses or deflections, in the critical cross section of the structure. In the case of pollution studies the concentrations are compared with limiting values, i.e. with critical concentrations. Such criteria are found in codes and regulations. This comparison is the usual method. Such a standard approach does not provide a suitable measure of uncertainty of the results, in particular in near critical situations. A better approach, which permits to include this uncertainty, is based on the theory of reliability, where the exceedance probability of the actual values exceeding the critical value is compared with a permissible exceedance probability (Plate and Davenport, 1995). By applying this method, the whole action chain is expressed analytically. The results from the wind tunnel study are empirical functions in the calculation, and the total result is a probability distribution of the outcome of the chain of processes.
6. Conclusions

Modelling of wind effects in urban environment is required for environmentally sound urban planning. However, in many cases it is not necessary to study the flow field in detail. Detailed model studies should only be performed if they yield information which actually can improve planning. Therefore, a hierarchy of models is proposed consisting of three categories: screening models, planning models for local situations, and far field models. Wind tunnel studies are useful for the first two categories: to further develop screening models through basic research, and to evaluate critical situations of wind loadings and concentrations. But these studies should be a link of the action chain of Fig. 6. Only if all links are considered in their joint action one obtains a decision problem which is complete and permits a consistent evaluation of the effects of wind loads of any kind. All examples shown could (and should) be used in this way.

Field investigations, wind tunnel studies and numerical models are complementary tools for urban planning. By accepting the limitations of different methods, and using physical or mathematical models where appropriate, wind tunnel modellers, meteorologists, and city planners should work together in planning modern, pollution free cities, with buildings that are designed to resist the loads and shape the wind field according to local climate conditions.

References


