VENTILATION TECHNOLOGIES IN URBAN AREAS

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ASSESSING NATURAL URBAN VENTILATION THROUGH AN INTEGRATED MODEL

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SYNOPSIS

The paper presents further then an integrated model the supporting methodology that allows to assess natural urban ventilation conditions both outside and inside constructions.
Though some particular aspects and procedures can be complex and time consuming the general structure is quite simple:
1. to establish wind regimes as a boundary condition - information can come from wind measurements at undisturbed areas like airports;
2. to integrate these regimes within the site - using numerical models to transfer information to the site;
3. to assess local wind velocities and pressures - promoting wind tunnel tests over physical models reproducing at a convenient scale its main characteristics;
4. to estimate ventilation rates - outside, from measurements, and inside, computing internal flow rates as dictated by both external and internal conditions.
Results can go from drawing general patterns of ground level winds, allowing to assess external ventilation and comfort conditions for pedestrians, to a computation of the flows and air proprieties, promoted inside a room taking into account small heat sources and sinks as well as the external conditions imposed by the wind.

LIST OF SYMBOLS

A area	h heat conductance	T temperature
C_{pk} pres coef. out. k opening	H height	U velocity
cp_{ar} specific heat of air	P pressure	ρ density
g gravity acceleration	Q heat power release	ζ head loss coef.

1. INTRODUCTION

In the middle of the 70's LNEC Applied Dynamics Division (NDA) promote its first works on natural ventilation in urban areas when pressure distributions were assessed in a physical model of Caracas Parque Central, Venezuela, and, further from static and dynamic wind loads, locations for natural ventilation intakes and exhaust of kitchens and sanitary rooms were defined taking into account the local wind regimes (*1*). By the end of the 70's and again for Caracas urban planners of Morellos, La Hoyada e Carabobo physical models were installed in the wind tunnel and the work was extended to assess external (ground level) ventilation conditions namely regarding pedestrian comfort (*2*). The beginning of the 80's brought out the development of the first numerical models based on integral equations and using data from wind tunnel tests (*3*) and by mid 80's the first numerical models based in differential equations were developed (*4*).

Along the years windows, doors and facades, static ventilators, ..., together with all types of construction components have been tested both in Laboratory facilities and *in situ* and results collected, treated and included in what is now a large data base at LNEC Behaviour of Construction Components Division (NCCp). Air tightness, for windows (*5*) and facades (*6*) and pressure coefficients for static ventilators (*7*) are included in that data.

In the late 80's fire studies in buildings allows for the construction of a new outdoor test facility simulating at a scale not smaller then 1:1.5 compartments of a house and their communications both internal and to the exterior (*8*) and, at the same time, a new wind tunnel of the Boundary Layer type with a large test chamber was built in order to develop studies where large areas and complex terrain were an important issue (*9*). Furthermore new numerical models were adopted or developed (*10*).

So being we consider that conditions are now established in such a way that an integrated approach to the study of natural ventilation in urban areas is available. The integrated model comprises both physical, at large and small scales, and numerical, integral and differential, models. Furthermore it is being developed both in time and frequency domains.

2. METHODOLOGY AND MODELS

Assess ventilation in urban areas demands the knowledge of the wind, the topology of the surroundings, the geometry of the site, the characteristics of the envelopes and the internal partitions and systems.

Wind information can be transferred through numerical modelling from undisturbed area like nearby airports to the site and used as a boundary condition to test in the Boundary Layer wind tunnel not only the pressure distribution of the specific building but also the general patterns of flow around it.

Window and facade characteristics can be measured at full scale in the test facilities the same applying for specific equipment like static ventilators tested in the wind tunnel.

Information can then be integrated with internal characteristics and internal heat sources, or sinks, so that numerical models both integral and differential can give a general idea of the internal flow patterns, the integral models providing a first approach for a complete description of the internal flow in a room.

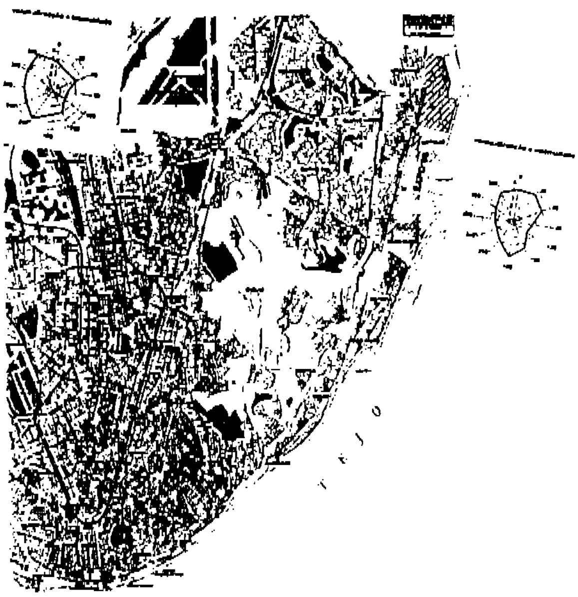
Turbulence and its effects on ventilation rates can be analysed both in the time and in the frequency domain. Local values can be measured over the physical models and both time series and its statistical proprieties and power spectral density functions can be estimate.

This information allows to proceed to a time step integration either directly or through the generation of synthetic time series from the "spectra" and so assessing the time variation of the ventilation rates that can then be characterised either in statistical terms or in the frequency domain. This second possibility, now under development, aims to define appropriate transfer functions for the internal flows.

Case studies where one or various of the different experiments, software and procedures referred will be presented to illustrate the present state of the integrated model.

2.1 Wind Regimes

Figure 1 presents the wind rose as measured along a year (hourly mean velocities) for Lisbon airport as well as the result of its transposition for the EXPO'98 area assuming the equivalent roughness of the city as defined from its bouroughs, quarters, type of construction, ... and the orography (figure 2) (*11*). Since the height considered is clearly above the mean height of the buildings the information can be used as a boundary condition for the site (*12*). The software used, WAsP (*13*), is currently adopted by those working in the market of wind energy, though some additional information has to be considered. Normal inputs would be the wind raw data - velocity and direction - and the orography and roughness class of the terrain.



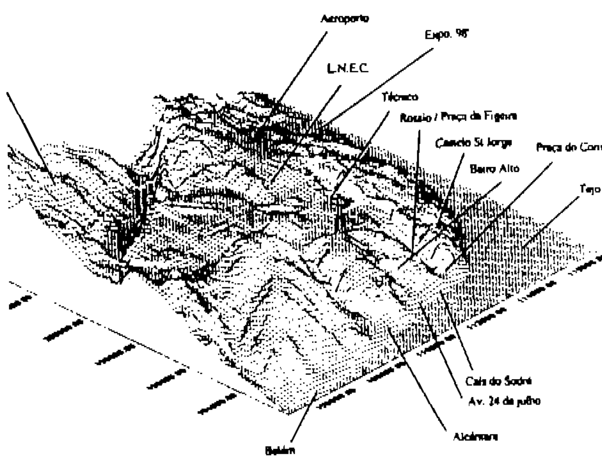


Fig. 1 Wind regimes in Lisbon airport and EXPO'98 Fig. 2 Lisbon orography

2.2 Local Wind Patterns

Figure 3 presents general lay-out of the EXPO'98 area, in Lisbon, as from a model built at 1:2500 scale and installed in the wind tunnel, the flow field at ground level being measured through the erosion technique (*14*) for different wind incidences (*15*). Values are presented in non-dimensional form as a relation between the local velocity and that that will be observed if no constructions were presented at the site.

It is also possible to use non distorted scaled models of large areas in the BL wind tunnel and reproduce details (typical are 5 m obstacles) allowing for the flow to develop as it runs over the model from a very clear boundary condition upstream (for instance the sea (*16*)).

2.3 Pressure Distributions and Components Characteristics

Pressure distribution can be measured over the external walls of models equipped with pressure taps as is the case of the Multiusos pavilion represented in figure 4 (*17*) the neighbourhood of which was also reproduced in the wind tunnel. Boundary Layers not only

with velocity and turbulence intensity profiles but reproducing length and time scales can be generated either through natural evolution or through the Couningham technique (*18*).
Results are normally expressed in terms of mean pressure coefficients.
In what concerns flow characteristics of components like windows and doors, glass facades, ... and ventilators tests in LNEC facilities allow to assess those (*19*), (*20*). Figure 5 shows a large glass facade tested (*21*).

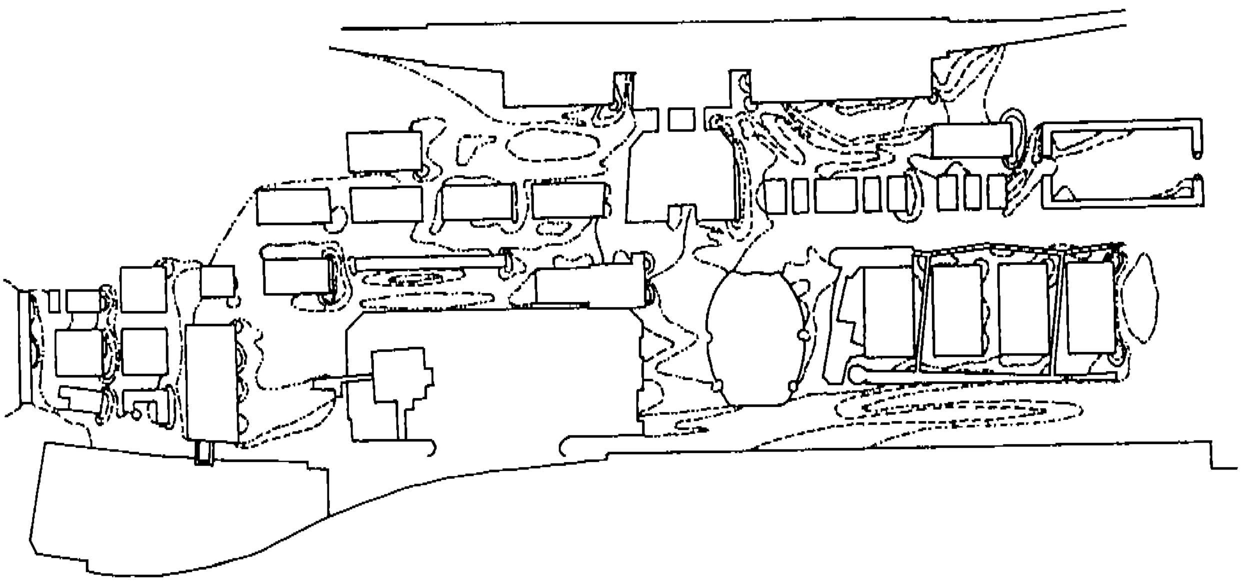


Fig. 3 Ground level winds on EXPO'98 for North incidence (prevailing summer winds)

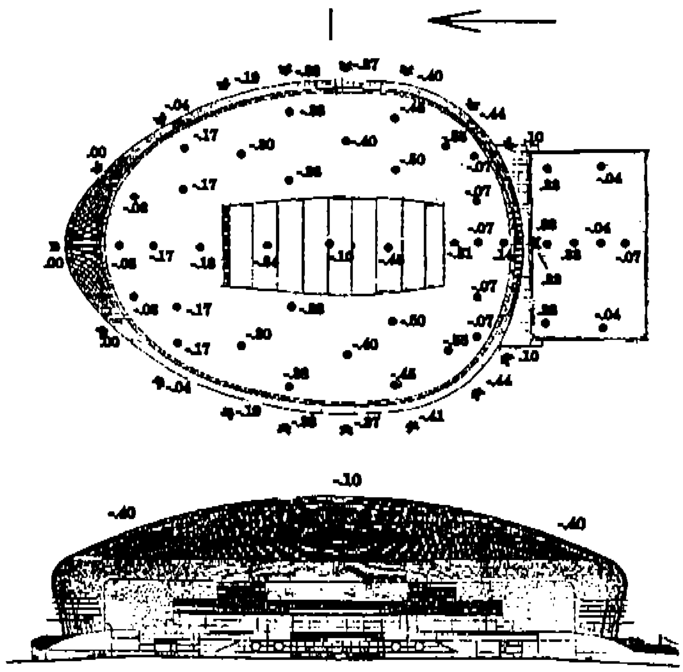


Fig. 4 Pressure over Multiusos pavilion at EXPO'98 for wind blowing from East

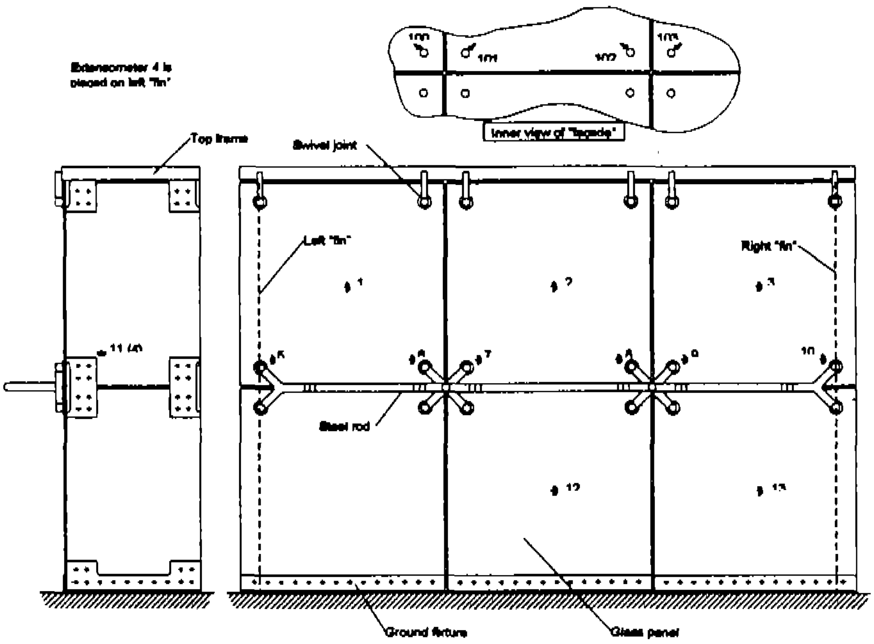


Fig 5 Section of the facade of Lisbon Oceanarium at EXPO'98 tested

2.4 Ventilation Rates

An analytical model for the prediction of ventilation rates, internal pressures and temperatures as influenced by the combined effects of natural wind action and heat generation or removal has been developed (*22*). Model inputs are external pressure coefficients, head loss coefficients of the openings and thermal conductance of walls and roofs, assumed to be known from experimental data.

$$\sum_{kl} U_{kl} A_{kl} = 0$$

$$\sum_{l} \sum_{kl} U_{kl} A_{kl} = 0$$

$$(\Delta\rho_l H_{kl} - \Delta\rho_l' H_{kl}')g + (\Delta p_l - \Delta p_l') - \varsigma_{kl} \tfrac{1}{2} \rho_0 U_{kl} |U_{kl}| = 0$$

$$\Delta\rho_l H_{kl} g + (\tfrac{1}{2} \rho_0 U_o^2 C_{pkl} - \Delta p_{l)} - \varsigma_{kl} \tfrac{1}{2} \rho_0 U_{kl} |U_{kl}| = 0$$

$$Q_l + \sum_{kl} \rho_0 c p_{ar} U_{kl} A_{kl} \Delta T_l + \sum_{ll} h_{ll} A_{ll} (\Delta T_l - \Delta T_l') = 0$$

$$\sum_{l} Q_l + \sum_{l} \sum_{kl} \rho_0 c p_{ar} U_{kl} A_{kl} \Delta T_l + \sum_{ll} h_{ll} A_{ll} (\Delta T_l - \Delta T_l') = 0$$

$$U_{kl} + U_{kl}' = 0$$

$$\frac{\Delta\rho_l}{\rho_0} + \frac{\Delta T_l}{T_0} = 0$$

Basic equations represent an integral balances of:
mass - for each room and for the whole building;
momentum - for each opening (expressed in terms of the Bernouilli equation);
energy - for each room and again for the whole building.
To these to sets of equations are added:

state equation - relating temperature variations with density variations thus allowing to represent buoyancy as a pressure difference in the momentum equation;
velocity compatibility - expressing that the flow through a communicating opening is the same as seen from both interconnected rooms.

2.5 Internal Flow Patterns

Internal flow patterns can be assessed through a rational approach combining 3D numerical simulation of the thermal and dynamic governing equations by means of a κ–ε two equation turbulence model with experimental data on wind pressure and pressure drop coefficients through the openings.
The equations can be written as follows (*23*)

$$\frac{\partial U_i}{\partial x_i} = 0$$

$$\frac{\partial}{\partial x_i}\rho U_i U_j - \frac{\partial}{\partial x_i}\left[\mu_t\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\right] + \frac{\partial P^*}{\partial x_j} + (\rho - \rho_0)g_j = 0$$

$$\frac{\partial}{\partial x_i}\rho U_i T - \frac{\partial}{\partial x_i}\left[\frac{\mu_t}{\Pr_t}\frac{\partial T}{\partial x_i}\right] - S_T = 0$$

$$\frac{\partial}{\partial x_i}\rho U_i \kappa - \frac{\partial}{\partial x_i}\left[\frac{\mu_t}{\Pr_\kappa}\frac{\partial \kappa}{\partial x_i}\right] - G - B + \rho\varepsilon = 0$$

$$\frac{\partial}{\partial x_i}\rho U_i \varepsilon - \frac{\partial}{\partial x_i}\left[\frac{\mu_t}{\Pr_\varepsilon}\frac{\partial \varepsilon}{\partial x_i}\right] - C_1\frac{\varepsilon}{\kappa}(G + B)(1 + C_3 R_f) - C_2\rho\frac{\varepsilon^2}{\kappa} = 0$$

$$\mu_t = \rho C_\mu \frac{\kappa^2}{\varepsilon}; G = \mu_t \frac{\partial U_i}{\partial x_j}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right); B = \beta g_i \frac{\mu_t}{\Pr_t}\frac{\partial T}{\partial x_i};$$

$$\beta = -\frac{1}{\rho}\frac{\partial \rho}{\partial T}; P^* = P + \frac{2}{3}\kappa$$

with
C_μ=0.09; C_1=1.44; C_2=1.92; Pr_κ=1.0; Pr_ε=1.3; Pr_t=0.7
In the form presented the momentum equations are subtracted by the static pressure equations, $\partial P_0 / \partial x_{ji} + \rho_0 g_j = 0$ to show the nature of the buoyant term $(\rho - \rho_0)g_j$.
In the transport equation for R_f is a flux Richardson number defined as $R_f = 0.5B_l/(B+G)$, B_l being the buoyancy production of only the lateral energy components, and C_3 is a numerical constant equal to 0.8.
Boundary conditions were established for openings - assuming the outside temperature and pressure as derived from the wind dynamic pressure times the local pressure coefficient and the compatibility equation through the opening is expressed in terms of a head loss coefficient - walls - the generalised log law was adopted and the conduction of heat through the wall assumed as usual - heat sources or sinks - considered in terms of its power as delivered in each cell.
The model initially developed for one room was further developed to allow the simultaneous computation in parallel of several rooms and then building a compatibility condition at each internal connection (*24*). Furthermore this model can now simulate the local combustion and the generation and transport of combustion products, namely soot and comply with its main aim - fire simulation.

2.6 Other Features of the Integral Model

The integral model already presented has been refined along the years and is now able to comply with problems like the transport of diluted substances including moisture (*25*) and its possible phase changes; is able to consider crack and other laminar (or at least no turbulent) flows (*26*) and to estimate the effects of wind turbulence as derived from power spectral density of turbulent velocity fluctuations and longitudinal and transverse correlation of gusts (*27*). Now under development is a model allowing to generate synthetic time series from the "spectra" (*28*) and to estimate through a step by step procedure that includes the ventilation transfer function of rooms time variations of air fluxes as induced in natural ventilation systems.

2.7 Experimental and Numerical Results

Validation of the methodology is now under way as a whole though for most of the procedures fair matches can be find between results arriving from experimental work and numerical modelling (29), (30), (31).

3. CONCLUSIONS

A reliable methodology and a set of procedures have been established in order to assess natural urban ventilation conditions based upon numerical modelling and wind tunnel tests over physical models reproducing at scale the main features of the area provided that appropriate boundary conditions for the flow (incidence, ABL characteristics) have been established. Sound data for component characteristics, based in experimental tests both in Laboratory facilities and on prototypes must be used.

Adoption of new models based on description of the external flow in the frequency domain and on appropriate transfer functions defined for each room looks promising.

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