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Modeling Parameters for Boundary-Layer Wind Tunnel Studies of Natural Ventilation

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ABSTRACT

Reliable surface pressure and indoor wind speed data from model buildings in boundary layer wind tunnels can only be expected if appropriate modeling parameters are considered carefully. Modeling parameters to examine when planning boundary layer wind tunnel studies of indoor airflow and external surface pressures due to wind are identified, and criteria for assessment are suggested.

INTRODUCTION

Smith (1951) was possibly the first person to study airflow through model buildings in a simple wind tunnel. He studied airflow through school classroom window openings. He suggested the use of wind speed coefficients referenced to outdoor wind speed for estimating ventilation. This work was carried out at the Texas Engineering Experiment Station. Similar studies were carried out by Weston (1954) on factories in Australia and by Wannenburg (1957) on school classrooms in South Africa.

With the benefit of hindsight, it is clear now that the wind tunnel modeling techniques used for earlier studies must have caused significant errors in the data obtained. There has been rapid development of boundary layer wind tunnel techniques since Jensen's pioneering work in 1958. It is now time that wind tunnels be reassessed as a tool to assist in the estimation of natural ventilation due to wind and the modeling parameters necessary for reliable data publicized.

Boundary layer wind tunnels can be used to determine:

1. Data on local mean hourly wind speeds and directions at a site relative to long-term wind data from a nearby meteorological recording site.
2. Influence of nearby obstructions, topographic features, or vegetation on local wind speeds.
3. Influence of architectural features such as extended eaves, sun-screen devices, or wall projections on surface pressure distribution around a building and indoor airflow.
4. Influence of size, proportion, and location of openings in a building on indoor airflow pattern and external pressure distribution.

Current boundary layer wind tunnel techniques are sufficiently accurate for ventilation design purposes according to full-scale correlation studies by Vickery (1981) and are continually being refined. Some wind tunnel techniques for determining influences of vegetation on local winds by White (1954) need further correlation of model and full-scale studies to determine their order of accuracy.

Modeling parameters for both the boundary layer airflow and the building model and its surroundings are often the determining factors in the accuracy of data from wind tunnel studies.

This paper describes boundary layer wind tunnel modeling parameters that need careful consideration when planning a boundary layer wind tunnel study of natural indoor ventilation to ensure reliable pressure and velocity data.

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WIND TUNNEL MODELING PARAMETERS FOR INDOOR VENTILATION STUDIES

These parameters can be divided into those related to the boundary layer airflow and those related to the model building and its immediate surroundings. Boundary layer modeling involves the generation of airflow through the wind tunnel, where the building model is to be placed, that reproduces at the appropriate scale:

-- mean vertical profile of longitudinal velocity,
-- vertical profile of turbulence intensity, and
-- power spectral density

of the full-scale wind for a particular direction at a site.

Mean Vertical Profile of Longitudinal Velocity

The mean vertical profile of longitudinal velocity of wind describes the gradual retarding effect of turbulence due to ground roughness and surface friction. This retardation of flow is greatest near the ground and decreases with height to zero at what is referred to as the "gradient height."

This retardation of wind near ground level (Figure 1), resulting in an increase in mean hourly wind velocity with height above ground, is described by the "log law" equation:

$$\frac{\bar{U}_z}{\bar{U}_r} = \frac{1}{k} C_g \ln \frac{z}{Z_o} \qquad (1)$$

where

$\bar{U}_z$ = Mean hourly longitudinal velocity (m/s) at height z (m) above ground roughness.
$\bar{U}_r$ = Mean hourly longitudinal velocity (m/s) at reference height r (m), (usually 10m).
k = Von Karman's constant (0.4 when using natural logarithms).
z = Height above ground roughness at which mean hourly longitudinal velocity is measured.
Z_o = Roughness length of surface (m).
C_g = Geostrophic drag coefficient determined from coriolis effect, surface friction, and mean hourly velocity at gradient height.
$\ln$ = Natural logarithm function.

Roughness elements for terrain on the earth's surface are approximately 5% to 10% of the mean height of obstructions above ground. Terrain roughness has been classified into four categories in most wind loading codes (Standards Association of Australia 1975). For example:

Category 1	Exposed open terrain with few or no obstructions of mean height less than 1.5 m (seacoasts and flat treeless plains).
Category 2	Open country with well scattered obstructions of mean height 1.5 to 10 m (most airports).
Category 3	Terrain with numerous closely spaced obstructions of mean height 3 to 20 meters (wooded suburban areas).
Category 4	Terrain with numerous large, closely spaced, tall obstructions of mean height 20 to 100 m (downtown area of urban centers).

Although the "log law" is theoretically sound, it is awkward to use. There is now preference for the widely used, more empirically based equation, referred to as the "power law":

$$\frac{\bar{U}_z}{\bar{U}_g} = \left[\frac{z}{Z_g} \right]^{\alpha} \qquad (2)$$

where

$\bar{U}_z$ = Mean hourly longitudinal velocity (m/s) at height z (m) above surface roughness.
$\bar{U}_g$ = Mean hourly longitudinal velocity (m/s) at gradient height.
z = Height above rough surface (m).
Z_g = Gradient height (m) characteristic of terrain roughness.
α = An exponent characteristic of terrain roughness.

Typical values for gradient height Z_g and exponent "α" for a range of terrain roughnesses are indicated in Table 1. The "power law" is not as well suited to describing the mean vertical profile of longitudinal velocity in the lower part of the earth's boundary layer as the "log law" but differences between profiles from each law is small (Aynsley et al.1977). With the exception of single isolated buildings on flat open terrain, neither law is applicable below the height of obstructions where airflow is determined by geometric configuration of adjacent obstructions.

It is essential in the case of tall buildings or low isolated buildings in smooth terrain that the length scale (height) of the mean hourly vertical profile match the length scale of the building model being studied.

The case of low buildings closely surrounded by similar sized buildings or roughness elements is less clear. Full-scale studies suggest that local flow fields associated with adjacent buildings or roughness elements dominate flow around such buildings, and the influence of the mean velocity profile is less detectable.

Turbulence Intensity

This characteristic of turbulent boundary layer airflow is the ratio at any point of the root mean square of the fluctuating component of flow, $\sqrt{\overline{U}'^2}$, to the mean velocity, $\overline{U}$, measured in the same direction. The longitudinal turbulence intensity is most commonly indicated for wind tunnel boundary layer flow. This decreases with height above typical suburban terrain from approximately 0.3 close to the surface to about 0.15 at a height of 100 m (Figure 1).

Vertical turbulence intensities also decrease with height above terrain roughness, but are typically less than the corresponding longitudinal turbulence intensities (Figure 1) (Aynsley et al. 1977, p. 73).

Power Spectral Density

Power spectral density, Su(n), is a measure of the fluctuation characteristics of turbulence expressed in terms of the power spectrum of turbulence and the associated probability distributions. Spectra for vertical and longitudinal components of turbulence close to the earth's surface during strong winds have been fitted to universal functions suggested by Davenport(1961)(Figure 1).

$$\frac{n\,Su(n)}{\overline{U}'^2} = \frac{nL}{\overline{U}} \qquad (3)$$

where

$n\,Su(n)$ = power per unit interval of frequency n of the velocity u.
$\overline{U}'^2$ = mean square value of the fluctuating component of velocity u'(m/s).
$\overline{U}$ = mean value of velocity u (m/s).
L = length scale (m).

Modeling Parameters for Buildings and their Immediate Surroundings

These parameters can be grouped into six considerations:

- Wind tunnel blockage
- Length scale
- Ability to reproduce small architectural details
- Modeling surrounding environment
- Reynolds number influences
- Time scaling for measurements

Wind Tunnel Blockage. There is no fixed criteria for wind tunnel blockage, that is, the percentage of the cross-sectional area of the enclosed wind tunnel test section occupied by models, except to say it should be as small as possible. Most experts recommend blockage less than 3%, which causes increases in windward to leeward pressure differences of approximately 10%. Blockage of 10% causes pressure difference increase errors in the order of 50%. Many recent wind tunnel studies keep blockage down to 1.5% or 2% (McKeon and Melbourne 1971). Some wind tunnels have test section roofs that can be raised to compensate for tunnel blockage, or partially open test sections with no roof at all as in the case of blower type wind tunnels.

Data from some studies in the early 1960s where blockage can be seen from photographs to be in the order of 30% to 40% are now considered invalid.

Length Scale Criteria. From the previous discussion of blockage, it can be seen there is good reason to keep models small. Working against this is the need to be able to reproduce architectural features that are known to influence surface flows around buildings such as sun shades, screens, projecting columns, beams, and eaves. The result of these opposing requirements has been a growing number of large boundary layer wind tunnels with cross sections of 5 square meters or more, which allow large city buildings and their surroundings to be modeled at scales between 1:200 and 1:500 and smaller residential buildings to scales between 1:100 and 1:150 while remaining within acceptable blockage levels. This chosen length scale for the model must correspond with the height scale of the simulated boundary layer flow in the wind tunnel, as discussd previously.

One situation in which much smaller scales, of say 1:2000, are used is in topographic models for correlating data from existing long-term meteorological recording sites with a temporary reference location closer to projects to be studied (Holmes et al. 1979).

Modeling a Building's Immediate Surroundings. Airflow patterns adjacent to buildings, particularly near ground level, are influenced by solid obstructions in the immediate vicinity. To ensure that similar flow patterns are reproduced in wind tunnel studies, these obstructions need to be modeled. Recommendations of the extent of this modeling vary from a radius of 10 building heights in low-rise buildings to approximately 700 metres radius in the case of tall buildings surrounded by generally lower buildings (Vickery 1981). Circular bases for this detailed local environment model are convenient, allowing its rotation in the wind tunnel to simulate a range of wind directions.

Outside this local environment model, upstream in the wind tunnel, roughness elements on the tunnel floor often do not reflect the physical obstructions on the ground, but only the general roughness needed to reproduce the boundary layer flow characteristics for each terrain over which the wind from a given direction approaches the model under test.

Reynolds Number Considerations. The Reynolds Number at a point in fluid flow is a measure of the ratio of "inertia force" to "viscous force" in the fluid at that point (Aynsley et al. 1977).

$$Re = \frac{\rho U L}{\mu} \qquad (4)$$

where

Re = Reynolds Number
ρ = fluid density (kg/m^3)
U = free stream velocity (m/s)
L = characteristic length (m) (crosswind dimension)
μ = dynamic viscosity of fluid (kg/m.s)

This ratio can be used to identify flow conditions as increases in velocity cause the boundary layer flow to change, from laminar at low velocities where viscous forces dominate, through a transition condition where bursts of turbulence occur, to fully turbulent flow. Flow patterns over a smooth curved surface, such as a circular rod, and corresponding drag coefficients, C_D, change significantly with Reynolds Number (Figure 2). This is due to the shifting of points of separation of the boundary layer on the surface of the object with changes in velocity. Sharp corners on objects will cause separation of the surface boundary layer on the surface of the object will continue to occur at the sharp corners. This means that for most buildings of rectangular form, the relative velocities within airflow patterns and their associated relative surface distributions remain constant over a wide range of velocities. Or in other words, flow patterns around typical flat-surfaced, sharp-edged building forms (bluff bodies) and their corresponding drag coefficients do not change significantly with large changes in Reynolds Numbers (Figure 2). It is this flow behavior that permits useful pressure and velocity data to be obtained from boundary layer wind tunnel studies without operating the tunnel at the very high speeds necessary for strict similitude of Reynolds Numbers in the model and full-scale flows. As the kinematic viscosity and density properties of air in the tunnel and around the buildings are likely to be similar to the wind tunnel air, "velocity" is the only parameter available to adjust to match full-scale and model flow Reynolds numbers.

If an attempt was made to maintain Reynolds number, the air velocity in the wind tunnel would need to be increased from the full-scale velocity of interest, by a factor of say, 250, equal to the inverse of the model scale, which will probably be 1:250. Such an air velocity would normally be beyond the operating speeds of a boundary layer wind tunnel and in any case would also be above the threshold of flow distortion due to compression effects in the flow (approximately 0.3 of Mach 1).

As a result of the considerations above, it is accepted practice to test bluff body models in boundary layer airflow velocities significantly lower than those required to maintain strict similitude with respect to Reynolds Number. These distortions from strict similitude make it essential that all data from such studies be in the form of dimensionless ratios (pressure and velocity coefficients) based on a reference that can be related to full-scale conditions.

Where flow data are required around smooth curved elements that are known to be Reynolds Number-dependent, distorted model scales are sometimes used. An example is the use of full-scale insect screening on wind tunnel house models described by Vickery (1981).

Time Scaling. Pressure fluctuations on windward faces of bluff bodies are largely influenced by turbulence in the approaching airflow. Pressure fluctuations on leeward faces of bluff bodies are influenced mainly by periodic vortex shedding associated with the wake. Where time scaling is necessary to evaluate fluctuating components of surface pressures, or for considerations of appropriate averaging periods for pressure data, this is done via the Strouhal Numbers (reduced vortex shedding frequency) associated with bluff shapes.

$$S = \frac{nL}{\overline{U}} \tag{5}$$

where

S = Strouhal Number
n = frequency of vortex shedding in wake (number/second)
L = characteristic length (cross flow dimension [m])
$\overline{U}$ = mean velocity (m/s)

from this the time scale ratio is:

$$T_r = \frac{L_r}{\overline{U}_r} \tag{6}$$

where

T_r = time ratio of model to full-scale
L_r = length scale ratio, model to full-scale
$\overline{U}_r$ = mean velocity ratio, model to full-scale

For a variety of reasons, including the characteristic time scale distribution of wind energy, mean hourly velocities and pressures are the common standard for infiltration or ventilation studies in wind tunnels.

FLUCTUATING COMPONENTS OF INDOOR PRESSURE AND VELOCITY

Where there is little indoor resistance to airflow, the fluctuating component of velocity can be measured in coefficient form using a fast response anemometer, such as a hot wire or hot film type. Interpreting the time scale of the velocity fluctuations is done using the time scaling ratios described above. Pressure fluctuations indoors can be measured using sensitive capacitance-type pressure transducers referenced to a convenient external pressure.

Where there is high indoor resistance to airflow but significant openings on the windward face of a building, pressurization of indoor air will occur. The resulting pressure fluctuations will follow the fluctuations in the dynamic pressure of the approaching wind (Holmes 1978).

INFILTRATION

If attempts are made to study infiltration directly in small-scale models, the problems of maintaining Reynolds number of flow through small cracks are encountered. To avoid these problems infiltration studies are usually carried out using surface pressures measured off solid wind tunnel models together with empirically based discharge coefficients in a discharge equation (Vickery 1981):

DISCUSSION

Boundary layer wind tunnels have been built at many universities and research establishments since the early 1960s. Most of these tunnels are large enough to be suited to ventilation studies of buildings and offer opportunities not frequently used for estimating ventilation due to wind. Improvements in wind tunnel techniques over the past two decades have been due to the development of a theoretical base for boundary layer and building modeling and correlation of data from model and full-scale studies.

Modeling parameters most commonly overlooked in wind tunnel studies are:
-- wind tunnel blockage effects,
-- Reynolds number effects,
-- inadequate modeling of surrounding environment.

If these and other parameters described in this paper are given adequate consideration, then data derived from wind tunnel studies can be expected to be within 10% of actual values (Vickery and Apperley 1973).

Many buildings designed to take advantage of natural indoor airflow due to wind for thermal comfort are relatively small and similar in scale to the surrounding buildings or vegetation. Buildings in these situations are influenced principally by local flow within the roughness layer. This allows strict modeling of the boundary to be relaxed but places more importance on the modeling of surrounding obstructions such as buildings and vegetation. It is still advisable to model mean vertical profile of velocity. Modeling of vegetation is a real challenge. Model trees made from wire mesh have been found satisfactory, but much more model and full-scale correlation work needs to be done. Model vegetation used on typical architectural presentation models of building projects is generally too solid and cannot be recommended.

Where interest is focussed on fluctuating components of pressure or velocity, particular care must be taken to accurately model the mean vertical profile of velocity, as well as turbulence intensity and power spectral density. Fluctuating indoor components of pressure and velocity measured in models can be expected to be within 10% of actual values where each opening is at least 1% of wall area in which it occurs (Aynsley 1980).

Direct wind tunnel studies of infiltration through small cracks are not feasible, due to the Reynolds number dependence of such openings and the small scales of building models. Wind tunnels have been used successfully to estimate infiltration, but indirectly, by providing surface pressure data from solid models that is then used in discharge equation (Vickery 1981).

Stack effect has not been discussed in this paper because of the major problems it poses in modeling similitude. Dimensionally, it is impossible to model all the relevent parameters at the same time in a wind tunnel (Reinhold 1982). Some studies have been done using distorted scales with some success but more research is needed. Stack effect can be incorporated in discharge equations mentioned in the previous paragraph.

CONCLUSIONS

There is now a broad consensus on the boundary layer wind tunnel modeling parameters that need consideration in order to obtain reliable mean hourly and fluctuating components of wind pressure and wind velocity (Reinhold 1982).

Modeling parameters for the boundary layer airflow in the tunnel are:
-- vertical profile of mean longitudinal velocity
-- vertical profile of turbulence intensity
-- power spectral density of the airflow.

Other parameters that relate to the model of the building being studied and its surroundings include:
-- wind tunnel blockage
-- model length scale
-- ability to reproduce architectural features at small scale
-- modeling of immediate surroundings
-- Reynolds number considerations
-- time scaling for measurements.

Provided these parameters are carefully considered, boundary layer wind tunnel studies offer a reliable source of mean and fluctuating components of wind pressure and velocity data in an around buildings.

REFERENCES

Aynsley, R.M. 1980. "Tropical housing comfort by natural airflow." Building Research and Practice. Vol.8, No.4, pp.242 253.

Aynsley, R.M.; Melbourne, W.; Vickery, B.J. 1977. Architectural aerodynamics. London: Applied Science.

Davenport, A.G. 1961. "The Spectrum of horizontal gustiness near the ground in high winds." Quarterly Journal of the Royal Meteorological Society. Vol.87, pp. 191 211.

Holmes, J.D. 1978. "Mean and fluctuating internal pressures induced by wind." James Cook Univ. Dept.of Civil and Systems Engineering, Wind Engineering Report No.5/78.

Holmes, J.D.; Walker, G.R.; Steen, W.E. 1979. "The Effect of an isolated hill on wind velocities near ground level – initial measurements." James Cook Univ.Dept. of Civil and Systems Engineering, Wind Engineering Report No.3/79.

Jensen, M. 1958. "The Model Law for phenomena in natural wind." Ingenioren International Ed.

Vol.2, pp. 121-158.

McKeon, R.J.; and Melbourne, W.J. 1971. "Wind Tunnel blockage effects and drag on bluff bodies in a rough wall boundary layer." Proceedings of the Third International Conference on Wind Effects on Buildings and Structures. Tokyo.

Reinhold, Timothy (ed). 1982. "Wind tunnel modeling for civil engineering applications". Proceedings of the International Workshop on Wind Tunnel Modeling Criteria and Techniques in Civil Engineering Applications. Gaithersburg.

Smith, E.G. 1951. "The feasibility of using models for predetermining natural ventilation." Texas Engineering Experiment Station Research Report, No.26.

Standards Association of Australia. 1975. "Wind Forces." Australian Standard, AS1170, part 2.

Vickery, B.J. 1981. "The use of the wind tunnel in the analysis of naturally ventilated structures." Proceedings AS/ISES International Passive/Hybrid Cooling Conference. Miami Beach.

Vickery, B.J.; and Apperley, L.W. 1973. "On the prediction and evaluation of the ground wind environment." The University of Sydney Dept.of Civil Engineering Research Report, R227.

Wannenburg, J.J.; and Van Straaten, J.F. 1957. "Wind Tunnel tests on scale model buildings as a means for studying ventilation and allied problems." Journal of the Institution of Heating and Ventilating Engineers, Vol.24, pp. 477-492.

Weston, E.T. 1954. "Natural ventilation in industrial-type buildings." Commonwealth Experimental Building Station Special Report, No.14.

White, R.F. 1954. "Effects of landscape development on the natural ventilation of buildings and their adjacent areas." Texas Engineering Experiment Station Research Report, No.45.

TABLE 1

Characteristics of Mean Hourly Vertical Profile of Longitudinal Velocity Related to Terrain.

Terrain Description	Terrain Category	Gradient Height (m)	Exponent α
Flat Treeless plain	1	250	0.11
Airports	2	300	0.15
Wooded suburban	3	400	0.25
High rise-urban	4	500	0.36

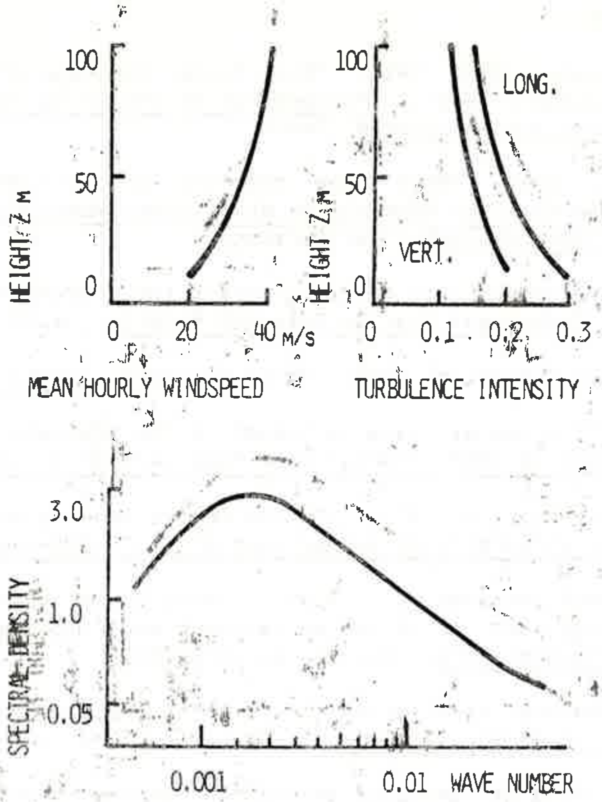

Figure 1. Characteristics of boundary layer developed over suburban terrain

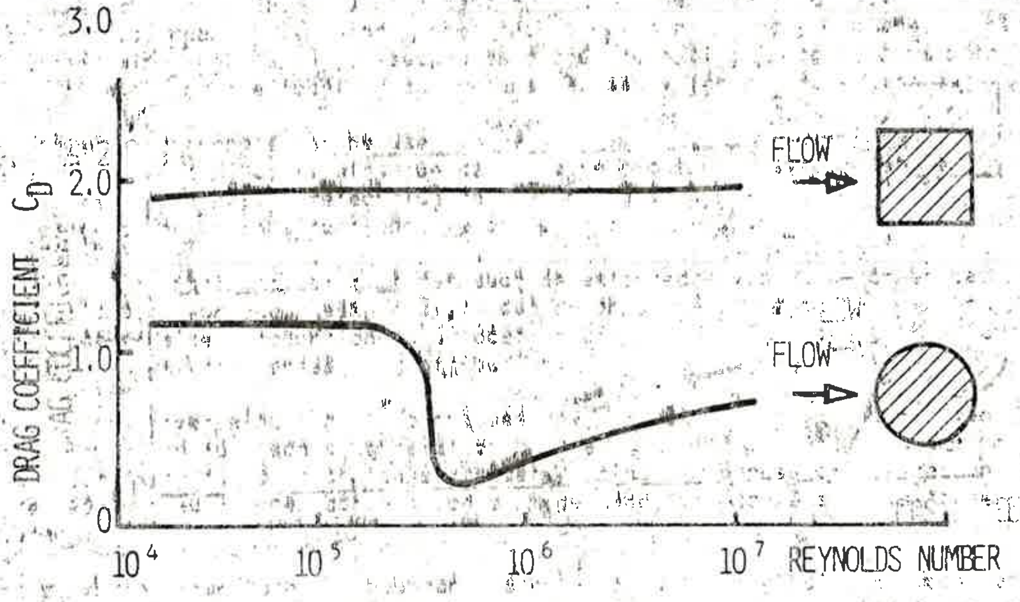

Figure 2. Comparison of Reynolds number influence on drag coefficients for bluff and curved rods