HI-85-35 No. 2

Estimating Comfort Cooling from Natural Wind inside Buildings Using Boundary-Layer Wind Tunnels

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ABSTRACT

Two techniques for estimating natural wind airflow through buildings for comfort cooling utilizing data derived from boundary layer wind tunnel studies are presented. One method is based on pressure and discharge coefficients. The other uses wind speed coefficients determined from model studies in a boundary layer wind tunnel.

INTRODUCTION

Man has utilized breezes to improve indoor summer comfort in warm humid climates since antiquity. Theories to enable the quantitative prediction of such airflow began and improved with developments in the discipline of fluid mechanics. A paper was presented by Shaw (1907) on the Laws of Ventilation at Cambridge University in 1907. Much later in 1951 a study (Smith 1951) was made of airflow through school classroom window openings in models in a simple wind tunnel, which suggested the use of wind speed coefficients referenced to outdoor wind speed for estimating ventilation. This work was done at Texas Engineering Experiment Station. Similar work was carried out soon after in Australia and South Africa (Weston 1954; Weston 1956; Wannenburg and Van Straaten 1957). It is now clear that the wind tunnel modeling techniques used for early studies must have caused significant errors in the data obtained. Given the rapid development of boundary layer wind tunnel techniques (Jensen and Franck 1965), it is now time to reassess wind tunnels as tools to assist in the estimation of natural ventilation due to wind.

Current engineering reference sources, such as ASHRAE Handbook -- 1981 fundamentals and IHVE Handbook suggest equations such as that below for estimating natural ventilation:

$$Q = E.A.V. \tag{1}$$

where

- Q is the airflow (m^3/s)
- E is the efficiency of an opening, ranging from 0.25 to 0.60
- A is the free area of an opening (m^2)
- and V is the mean external wind speed (m/s) (presumably at window height above ground).

The appealing simplicity of Equation 1 avoids the complex issues of gusting flow through a variety of openings in series and the lack of data on local mean external wind speeds close to the ground level. Other formulae include wind pressure differences across openings together with discharge coefficients. While some discharge coefficients are available from ducted flow studies, these relate to known pressure differences and steady flow and are not applicable to natural airflow through large openings in buildings. Wind tunnel studies (Aynsley 1979) have provided limited data of the type required; many more are needed.

Boundary layer wind tunnels can be used to determine:

1. Probabilistic data on local mean hourly wind speeds and directions at a site relative to long-term wind data from a nearby meteorological recording site (Aynsley et al. 1977).

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2. Influence of nearby obstructions, topographic features, or vegetation on local wind speeds (Holmes et al. 1979; White 1954).
3. Influence of architectural features such as extended eaves, sun-screen devices, or wall projections on surface pressure distribution around a building (Aynsley 1977).
4. Influences of size, proportion, and location of openings in a building on airflow pattern and pressure distribution (Aynsley 1979).

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

This paper describes:

1. Boundary layer wind tunnel modeling parameters that currently need consideration to ensure reliable data from tests.
2. Two methods of using probabilistic wind data to estimate airflow through buildings for summer thermal comfort of occupants. One method uses pressure difference / discharge coefficients, the other, wind speed coefficients.

WIND TUNNEL MODELING PARAMETERS FOR 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 around the building model that reproduces at the appropriate scale the following characteristics:

-- mean vertical profile of longitudinal velocity,
-- vertical profile of longitudinal velocity,
-- power spectral density,

of the full-scale wind for a particular direction at a site (Aynsley et al. 1977).

Modeling Parameters for Buildings and their Immediate Surroundings

These parameters can be grouped into six categories (Aynsley et al.1977):

-- wind tunnel blockage,
-- length scale,
-- ability to reproduce small architectural details,
-- modeling surrounding environment,
-- Reynolds number influences, and
-- time scaling for measurements.

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 and ventilation studies in wind tunnels (Vickery 1981).

SUMMER THERMAL COMFORT AND NATURAL AIR MOVEMENT

Advances in boundary layer wind tunnel techniques now permit estimates of the probability of natural airflow through buildings capable of restoring thermal comfort of occupants in warm environments. To make such estimates, probabilistic data is required on climatic parameters such as dry-bulb temperature, or mean radiant temperature, wet-bulb temperature or relative humidity, and local wind speeds and directions.

Two simple thermal comfort charts that relate the above variables are Effective Temperature and one by the writer based on Macfarlane's Thermal Comfort Zones (Macfarlane 1958) (Figure 1). Boundary layer wind tunnels provide a means of correlating long-term wind records from permanent meteorological stations, (Table 1) with local wind conditions at a building site.

ESTIMATING VENTILATION WITH PRESSURE DIFFERENCES AND DISCHARGE COEFFICIENTS

Discharge coefficients typify the empirical nature of many branches of fluid mechanics. Where complexity of flow eludes complete theoretical analysis, empirical methods are used. Empirical methods use coefficients derived from experiments to provide a means of design.

Discharge coefficients of openings only retain their specific empiric validity as long as they are used with their associated pressure difference. Quantifying discharge through window openings with a complex turbulent incident flow poses numerous problems. First, there is an almost endless variety of geometry and exposure conditions. For openings that happen to be in a windward orientation, the external dynamic pressure is a vector quantity with rapidly varying intensity and direction.

Unlike laminar flow in pipes, with natural airflow through buildings there is no conveniently defined reference for pressure differences across orifices. Negative pressures are generally even around leeward openings. Positive pressures around windward openings are influenced by local flow conditions and vary significantly around windward openings. On residential scale buildings, pressures are greater near the top of windward walls, but stagnation pressures beside the midheight of windward windows were found to be a good approximation of mean total pressures on windward openings (Aynsley 1977).

Typical average pressure difference coefficients across buildings at midheight of walls on six types of solid model houses are provided in Table 2 (Aynsley 1977).

Openings in Series

Flow through buildings generally occurs through at least two openings, inlet and outlet, in series or via branching paths where multiple inlets and/or outlets are present. In addition, where airflow resistance through a building is high, flow can branch at inlet openings with a major portion of incident airflow flowing around the building.

Considering the simplest case of flow between windward and leeward openings in series without internal branching, it can be shown from an energy equation for the flow that the effective pressure difference is between the total pressure at the windward opening and the static pressure at the leeward opening (Aynsley 1977).

As there are rarely detailed data on internal pressures in buildings, it is desirable to have discharge coefficients for combinations of openings in series related to the effective windward/leeward pressure difference. The combinations and permutations of such openings in series are almost unlimited. One approximate formula for discharge through openings in series, which makes use of typical discharge coefficients for individual openings without specific reference to the pressure differences across each opening, is (Aynsley 1977):

$$Q = \sqrt{\frac{(Cp_1 - Cp_{n+1})\,\bar{U}_z^2}{\frac{1}{Cd_1^2 A_1^2} + \frac{1}{Cd_2^2 A_2^2} + \dots \frac{1}{Cd_n^2 A_n^2}}} \qquad (2)$$

where

A_n is the square of the free area of opening number n (m^2)
Cd_n is the square of the discharge coefficient for opening number n
$\bar{U}_z^2$ is the square of the mean reference free external wind speed (m/s) at a height z, usually 10 m above ground
Q is the discharge (m^3/s)
Cp_1 is the coefficient of total pressure at the windward opening
Cp_{n+1} is the coefficient of total pressure at the leeward opening.

This equation covers most simple cross-ventilation situations such as houses and classrooms. An example of the application of this equation is provided in Appendix A.

For more complex flow conditions where internal branching of the flow occurs, the solution is more complex, involving the iterative solution of simultaneous equations with numerous coefficients, and is best done by computer. An example of such a calculation for infiltration in a high-rise office building is described by Vickery (1981).

Sources of Discharge Coefficients

Where internal airflow in buildings is forced to change direction frequently because of relative location of openings, resistance to flow increases and the use of a discharge coefficient of 0.65 for all openings was found to give an estimate of flow 2% greater than measured (Aynsley 1977).

In flow conditions with few changes in direction but large variations in opening sizes, use of a common 0.65 discharge coefficient for all internal openings and measured total to static pressure difference resulted in underestimation of measured flow by -16% to -29%, the average being -23.5%

In flow conditions with little resistance, such as a single cross-ventilated room with windward and leeward open louvered walls, the use of a discharge coefficient of 0.65 underestimated flow by -35% using the measured total to static pressure difference (Aynsley 1977).

In free flow conditions the discharge coefficients in Table 3 were found to be appropriate. Inclined incidence of airflow away from normal to windward openings reduced flow rate into such openings in proportion to the cosine of the angle of incidence up to 60 degrees. Above 60 degrees incidence, no clear relationship could be detected, but generally flow rate continued to decrease.

Pressure Differences

The pressure difference part of Equation 2 is referenced to the mean hourly dynamic pressure reference at a height 10 m above ground. This can be correlated with similar long term records at the closest meteorological recording station to generate local probabilistic data. Windward total pressure data at openings are not normally available, and the pressures normal to the building surface at the location of the opening, measured off a solid model, are usually used.

Typical variations between solid model windward/leeward surface pressure differences and windward total pressures/leeward static pressures measured at normal incidence to long walls on wind tunnel models of houses over a range of opening sizes are indicated in Figure 2. As flow rates are proportional to the square root of pressure differences, the use of solid model surface pressure data does not normally result in gross errors when openings are less than 5% or greater than 40% of wall area. Largest increases over solid models in pressure differences across houses occur near the ends of long windward walls (Figure 2) when openings are about 15% of wall area (Aynsley 1977). Use of solid model pressure differences under these conditions results in underestimation of airflow rate by 30%. Care should be taken in selection of pressure distribution data to ensure that the wind tunnel study followed acceptable modeling practice.

Most institutions with large boundary layer wind tunnel facilities have such data for a wide variety of building types, but it is usually on magnetic tape and requires data processing to yield the information in a convenient format. Often such pressure distribution data collected for wind loading purposes is taken from single isolated building models. There is much less surface pressure distribution data available on buildings surrounded by other buildings. In the case of tall office buildings, design consulting budgets often include boundary layer wind tunnel studies for wind loadings or environmental wind effects. These can be extended to collect surface pressure distribution data at little cost. Such a study and its correlation with full-scale observations is described by Dalgliesh, Templin, and Cooper (1980).

ESTIMATING VENTILATION USING MEAN WIND SPEED COEFFICIENTS

Given the availability of boundary layer wind tunnel facilities and funds for model studies, there is a more direct technique of estimating airflow inside buildings than discharge equations. Where internal spaces and building openings can be modeled accurately, internal airflow can be measured directly and related to probabilistic external wind data. This calls for model scales of at least 1:150 or bigger and small omnidirectional anemometers. For comfort purposes, flow direction is less important than air movement per se. While directional anemometer probes are used, they need to be rotated during the test to align them with the direction of air movement.

Mean Wind Speed Coefficients

Wind speed coefficients, C_v, are the ratio of the mean wind speed, $\overline{U}_1$, at a point of interest indoors, usually one metre above floor level, to the mean hourly wind speed, $\overline{U}_z$, at a specified reference height, z (usually 10 m), upstream from the building in the airflow undisturbed by the building so that:

$$C_v = \frac{\overline{U}_1}{\overline{U}_z} \tag{3}$$

where

C_v = mean wind speed coefficient

$\overline{U}_1$ = mean indoor wind speed at a point 1 m above floor level

$\overline{U}_z$ = mean external reference wind speed at a height z above ground (z is usually 10 m)

Some mean wind speed coefficients determined from a simple cross-ventilated model for wind speeds 1 m above floor level and related to 10 m reference wind speed are indicated in Figure 3.

A similar technique, described by Vickery and Apperley (1973) for predicting the probable frequency of strong wind gusts near ground level in urban terrain was found, from full-scale correlation, to have an accuracy in the order of plus or minus 10%. With careful modeling, similar accuracy should be possible in estimates of indoor wind speeds.

The wind speed coefficient approach is ideally suited to steady airflow through and around buildings of complex or unusual shape. A discharge coefficient approach for such a building would require a detailed wind tunnel study of wind pressure distributions at many locations over the model surfaces. It is much simpler to measure wind speed coefficients directly.

The principal advantage of the wind speed coefficient approach is that mean wind speed estimates can be obtained for any position at which a small anemometer can be located. A disadvantage is that larger, more detailed models are necessary than are necessary for wind pressure distribution studies. Components that deflect the airstream, such as louvers or tilting sashes, need to be modeled with extreme care due to their significant influence on indoor airflow patterns.

The simplicity of the velocity coefficient method for estimating air velocities in buildings is appealing; however, the time and expense involved in wind tunnel studies to determine wind speed coefficients restricts its application to many low budget buildings. Most studies on low-cost buildings have been made in research programs at government research stations and at universities. An example calculation estimating thermal comfort using wind speed coefficients is provided in Appendix B.

DISCUSSION

Boundary layer wind tunnels offer a means of obtaining accurate mean hourly probabilistic wind pressure data on building surfaces for use in estimating airflow through buildings from discharge type equations. The influence of local terrain and nearby buildings can be accounted for by incorporating such features in the wind tunnel models.

Given reliable pressure data, errors in estimates of natural ventilation when using pressure difference/discharge coefficients equations are most likely to arise from poor selection of discharge coefficients. Such errors tend to result in underestimates of ventilation where large openings and low flow resistance occur and provide a margin of safety when summer thermal comfort or air change rates are being considered (Aynsley 1977). More boundary layer wind tunnel testing to provide discharge coefficients for large openings in series would reduce this source of error. Where the purpose of the ventilation estimate is related to heat loss in winter, flow is through smaller cracks and openings and use of a discharge coefficient of 0.65 generally results in a slight overestimate of ventilation (Aynsley 1977). Lack of simultaneous data on all factors influencing thermal comfort of building occupants often limits such estimates to specific hours of the day, typically 9 a.m. and 3 p.m.

The principal advantage of the discharge equation approach to estimating natural ventilation is that, provided appropriate pressure and discharge coefficient data are available, estimates of airflow can be calculated in design offices without recourse to special wind tunnel tests.

A disadvantage of the discharge equation approach is that local mean velocities can only be estimated at points where the flow passes through openings. This limitation can be significant when the purpose of the ventilation estimate is assessment of thermal comfort of occupants in areas away from openings that may not be in the main airstream.

A mean wind speed coefficient approach to estimating natural ventilation inside buildings permits a more detailed study of indoor airflows, provided that model scales permit accurate modeling of openings and indoor space and appropriate placement of an anemometer probe. While this advantage is attractive to people seeking data for indoor comfort estimates, the method does require boundary layer wind tunnel tests to be performed.

CONCLUSIONS

There is now a broad consensus on the boundary layer wind tunnel modeling parameters needed to obtain reliable mean hourly surface pressure and mean hourly local wind velocity data.

Some modeling parameters relate to the boundary layer airflow in the tunnel. These parameters are:

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

Other parameters relate to the model of the building being studied and its surroundings. These parameters are:

- -- wind tunnel blockage,
- -- model length scale,
- -- ability to reproduce small architectural details,
- -- 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 surface pressure distributions on buildings and local mean wind speeds, which, if referenced to local long-term wind records, can be expressed in probabilistic form.

Pressures related to flow through openings in buildings differ from the surface pressures on solid models without openings. On some models of houses tested, this difference varied with the size of openings relative to wall areas and between houses on the ground and those raised some 2.3 meters above the ground.

Where estimates of natural ventilation through houses using a discharge equation use pressure differences measured from solid models, airflow rates through houses may be underestimated by up to 30%. As studies of this type have been limited to date, there is a need for further research in this area.

Discharge coefficients for wall openings in series need further study, particularly in the case of large wall openings and low internal flow resistance. Estimation of discharge coefficients for high resistance airflow paths through cracks and small openings is less critical as use of a discharge coefficient of 0.65 for all openings gives estimates of airflow sufficiently accurate for most purposes. Estimates of airflow through openings in buildings using discharge equations will continue to improve as more boundary layer wind tunnel test data on surface pressure distribution are published.

Use of mean wind speed coefficients for estimating airflow inside buildings is limited for design office use at present due to lack of published data. This method provides a direct technique for assessing indoor airflow where boundary layer wind tunnel facilities are available and model scales are large enough to permit detailed modeling of openings and internal spaces and placement of anemometer probes. Mean wind speed coefficients can be obtained for any point inside a model where an anemometer probe can be placed using this technique. This is an important advantage when airflow data are being used to assess summer thermal comfort of building occupants located away from openings in eddy zones.

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APPENDIX A

Example

Determine the extent to which natural ventilation is likely to maintain comfort in the living room of an isolated house raised 2.3 m above ground in Townsville at 3 p.m. during January using the discharge equation.

Climatic Data

3 p.m. 86 percentile average maximum dry-bulb temperature for January = 32.9°C
3 p.m. average relative humidity = 62%

Assuming adequate insulation is provided in the building envelope and windows and walls are shaded to control radiation, the minimum indoor airflow needed to restore thermal comfort for the above temperature and humidity from Figure 1 is 0.83 m/s.

Wind speed frequency and directions for Townsville at 3 p.m. during January are indicated in Table 1. It would be reasonable to expect these data to be representative of most Townsville suburbs, as there is no significant change in terrain over most of the suburban area.

Building Data

Orientation of rectangular plan, isolated high-set house (Type 3, Table 2) is with its long walls facing north and south. The living room is at the eastern end of the house with a sliding door on its north wall with a clear area of 2 m^2 and two sliding windows on its south wall each with a clear area of 0.5 m^2. Openings in living room walls:

Opening	Dimensions	Clear area of openings
Sliding door north-facing wall	2 m x 1 m	2.0 m^2
Two sliding windows south-facing wall	1 m x 0.5 m each	1.0 m^2
Cross section of living room	3 m x 4 m	12.0 m^2

Method

NE winds : Wind incidence used 45 degrees.
Pressure coefficients at locations near openings at midheight of walls from Aynsley et al.(1977, p.197):

Windward	+0.33
Leeward	-0.38

Free area of windward opening = 2 m^2

Correction factor for 45 degrees incidence = cosine 45 degrees = 0.707

Corrected free area = 2 x 0.707 m^2 = 1.4 m^2

Discharge coefficient from Table 3 for windward opening with two edges common with the downwind space = 0.75

Free area of leeward openings = 1 m^2

Discharge coefficient for leeward openings from Table 3 with an Ao/A1 ratio of 0.08 = 0.63

Discharge Q m^3/s to achieve thermal comfort at the windward opening is the product of the effective area of the opening A1 Cosθ and the minimum wind speed for thermal comfort 0.83 m/s, that is:

$$= A_1 \cos\theta . \bar{U}_1$$
$$= 2 \times 0.707 \times 0.83$$
$$= 1.17 \ m^3/s$$

Equation 2 can be rearranged to solve for the wind speed 10 m above ground needed to achieve the above discharge rate and corresponding minimum indoor wind speed for thermal comfort:

$$\bar{U}_{10} = \sqrt{\frac{\dfrac{A_1 \cos\theta \ \bar{U}_1}{(Cp_1 - Cp_2)}}{\dfrac{1}{Cd_1^2 A_1^2} + \dfrac{1}{Cd_2^2 A_2^2}}}$$

$$= \sqrt{\frac{\dfrac{1.17}{[0.30 - (-0.38)]}}{\dfrac{1}{0.75^2 \times 1.4^2} + \dfrac{1}{0.63^2 \times 1^2}}}$$

$$= 2.63 \ m/s$$

Discharge Q to achieve thermal comfort at the leeward openings is the product of the effective area of the opening and the minimum local wind speed needed for thermal comfort,

$$Q = A_2\bar{U}_2$$
$$= 1 \times 0.38$$
$$= 0.83 \ m/s$$

Solving for the 10 m wind speed to achieve this discharge rate as before:

$$\bar{U}_{10} = \sqrt{\frac{\dfrac{0.83}{[0.30 - (-0.38)]}}{\dfrac{1}{0.75^2 \times 1.4^2} + \dfrac{1}{0.63^2 \times 1^2}}}$$

$$= 1.87 \ m/s$$

Clearly for winds from the northeast, the governing 10 m wind speed requirement is 2.63 m/s for the windward opening, which falls within the 1.6 - 3.0 m/s 10 m wind speed interval on the wind frequency Table 1.

Summing the percentage occurrence of higher wind speed intervals 3.0 - 5.0 m/s of 14.3% and 5.0-8.0 m/s of 12.3% for the northeast direction gives a total of 26.6% of time.

When all wind directions are considered (Table A1) comfort is likely to be achieved near both windward and leeward openings for the 86 percentile dry-bulb temperature of 33°C and relative humidity of 62% for approximately 50% of the time at 3 p.m. during the month of January.

APPENDIX B

Example

Determine, using the mean wind speed coefficient technique, the likelihood of maintaining comfort by natural airflow in the living area of a single-story residence with extended eaves and end walls (Figure 3) in Townsville at 3 p.m. during January. Note that walls and ceilings are insulated or shaded to eliminate significant radiant heat gain to occupants.

Climatic Data

3 p.m., 86 percentile daily maximum dry-bulb temperature for January
= 32.9°C

3 p.m., monthly average relative humidity = 62%

Airflow needed to restore comfort from Figure 1
= 0.83 m/s

Mean Wind Speed Coefficients

Method: Using mean wind speed coefficient C_V of 0.72 for the living room indicated in Figure 3 for wind from the north, the wind speed, required at the reference height of 10 metres to ensure thermal comfort in the living room, can be calculated by substituting 0.83 m/s for the local indoor wind speed $\bar{U}_1$:

from Equation 3

$$\bar{U}_z \text{ (for comfort)} = \frac{0.83}{C_V} = 1.15 \text{ m/s}$$

By summing the frequency of occurrence of all wind speeds 10 metres above the ground, from Table 1, which exceed 1.15 m/s for winds from the north, an estimate of the percentage of time winds from the north would meet thermal comfort criteria in the living room, at 3 p.m. during January in Townsville is obtained.

From Table 1 percentage occurrences of northerly winds for all wind speed intervals exceeding 1.15 m/s are 3.9% for 1.5 to 3.0 m/s, 8.4% for 3.0 to 5.0 m/s, 2.6% for 5.0 to 8.0 m/s and 0.6% for 8.0 to 11.0 m/s, giving a total of 15.5% of time when northerly winds will restore comfort. This process is repeated (Table B1) for each wind direction until a total percentage is obtained of time during which comfort is likely to be maintained.

TABLE 1

Percentage Distribution of 10 m Winds at 3 p.m., Townsville, January

Wind Direction		Wind Speed Intervals m/s					Average Monthly Total % Occurrence
		0.5–1.5	1.5–3.0	3.0–5.0	5.0–8.0	8.0–11.0	
CALMS	0.6						0.6
NNE		0.6	2.6	1.9	3.2	–	8.4
NE		1.3	4.5	14.3	12.3	–	32.5
ENE		–	0.6	11.7	7.8	–	20.1
E		–	0.6	3.2	3.9	1.9	9.7
ESE		–	–	0.6	1.9	1.3	3.9
SE		–	0.6	1.9	–	–	2.6
SW		–	0.6	–	–	–	0.6
NW		–	–	1.3	–	–	1.3
NNW		–	1.3	1.9	0.6	–	3.9
N		0.6	3.9	8.4	2.6	0.6	16.2

TABLE 3

Typical Discharge Coefficients for Single Inlet or Intermediate Openings and Leeward Outlet Openings in Buildings

Description of Building Opening	Typical Range of Discharge Coefficients for Normal Incidence	Jet Characteristics
Small openings in thin walls less than 10% of wall area near center of wall	0.50 - 0.65	Small inertia due to small mass of air in jet
Openings 10-20% of wall area near the center of wall with downwind space	0.65 - 0.70	Significant inertia due to increased mass of air in jet
Openings 10-20% of wall with one edge common with downwind space such as doorway	0.70 - 0.80	Wall effect reduces energy losses on one side of jet
Openings similar in size to the cross-section of the downwind space	0.80 - 0.90	Wall effect around the perimeter of the jet significantly reduces turbulent energy losses

Ao/Ai (approx.)	Cd
0.0	0.63
0.2	0.64
0.4	0.67
0.6	0.71
0.8	0.81
1.0	1.00

Where: Ao = Free cross-sectional area of upstream flow
Ai = Free area of outlet opening
Cd = Discharge coefficient of opening

TABLE A1

Total Percentage of Time Thermal Comfort is likely Considering Winds from all Directions

Wind Direction	Incidence θ^o	Cp_1 (from Aynsley 1977)	Cp_2 (from Aynsley 1977)	A_1	$A_1 \cos \theta^o$	A_2	$A_2 \cos \theta^o$	Cd_1	Cd_2	Minimum Wind Speed Interval for Thermal Comfort (m/s)	% Occurrence of Thermal Comfort
NNE	22	0.36	0.0	2	1.8	1	-	0.75	0.63	5.0	3.2
NE	45	0.30	-0.38	2	1.4	1	-	0.75	0.63	3.0	26.6
ENE	67	0.14	-0.07	2	0.77	1	-	0.75	0.63	5.0	7.8
ESE	67	-0.07	0.14	2	-	1	0.38	0.64	0.70	14.0	-
SE	45	-0.38	0.30	2	-	1	0.71	0.64	0.70	5.0	-
SW	45	-0.16	0.0	2	-	1	0.71	0.64	0.70	11.0	-
NW	45	0.0	0.16	2	1.4	1	-	0.75	0.63	5.0	-
NNW	22	0.16	-0.07	2	1.8	1	-	0.75	0.63	5.0	0.6
N	0	0.55	-0.12	2	2.0	1	-	0.75	0.63	3.0	11.6
										Total %	49.8%

TABLE 2

Wind Pressure Difference Characteristics at Midheight of Walls on Six Types of Isolated Solid Models at Wind Incidences of Normal 30° and 45° to the Long Walls

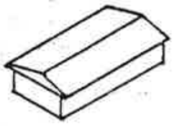
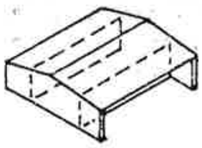
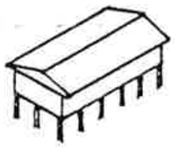
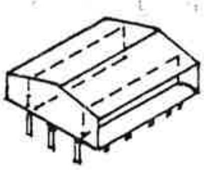
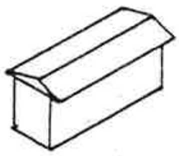
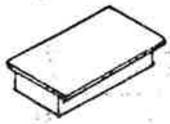
Model Features Note: Position on Long Walls; C=Center BE=Both Ends WE=Windward End LE=Leeward End	Model Type	Incidence to Long Wall	Average Pressure Diff. Coefft. Between Long Walls	Maximum Pressure Diff. Coefft. Between Opposite Points on Long Walls	Minimum Pressure Diff. Coefft. Between Opposite Points on Long Walls
	1	0°	0.49	0.56 C	0.42 BE
		30°	0.41	0.67 WE	0.10 LE
		45°	0.34	0.71 WE	-0.02 LE
		Average	0.41		
	2	0°	0.51	0.56 C	0.46 BE
		30°	0.66	0.71 WE	0.58 LE
		45°	0.58	0.63 C	0.52 C
		Average	0.58		
	3	0°	0.65	0.71 C	0.60 BE
		30°	0.58	0.79 WE	0.33 LE
		45°	0.43	0.81 WE	0.00 LE
		Average	0.55		
	4	0°	0.81	0.85 BE	0.77 C
		30°	0.67	0.75 LE	0.50 WE
		45°	0.75	0.81 LE	0.73 BE
		Average	0.74		
	5	0°	0.61	0.69 C	0.52 BE
		30°	0.33	0.37 C	0.24 WE
		45°	0.31	0.42 C	0.12 LE
		Average	0.42		
	6	0°	0.51	0.58 C	0.44 BE
		30°	0.42	0.69 WE	0.08 LE
		45°	0.35	0.71 WE	0.00 LE
		Average	0.43		

TABLE B1

Total Percentage of Time Thermal Comfort Criteria are Likely to be Maintained by Wind from all Directions

Wind Direction	Velocity Coefficients From Fig.3	10 m Wind Speed Needed to Give 0.83 m/s indoors	Cumulative Percentage of Time Wind Speeds Exceed Speed Needed for Thermal Comfort
N	0.72	1.5	15.5
NNE	0.90	0.92	7.8
NE	0.95	0.87	31.2
ENE	0.85	0.98	20.1
E	negligible	-	negligible
ESE	0.85	0.98	3.9
SE	0.95	0.87	2.6
SSE	0.90	0.92	negligible
S	0.72	1.15	"
SSW	0.70	1.19	"
SW	0.52	1.60	0.6
WSW	negligible	-	negligible
W	"	-	"
WNW	"	-	"
NW	0.52	1.60	1.3
NNW	0.70	1.19	3.9
			86.9%

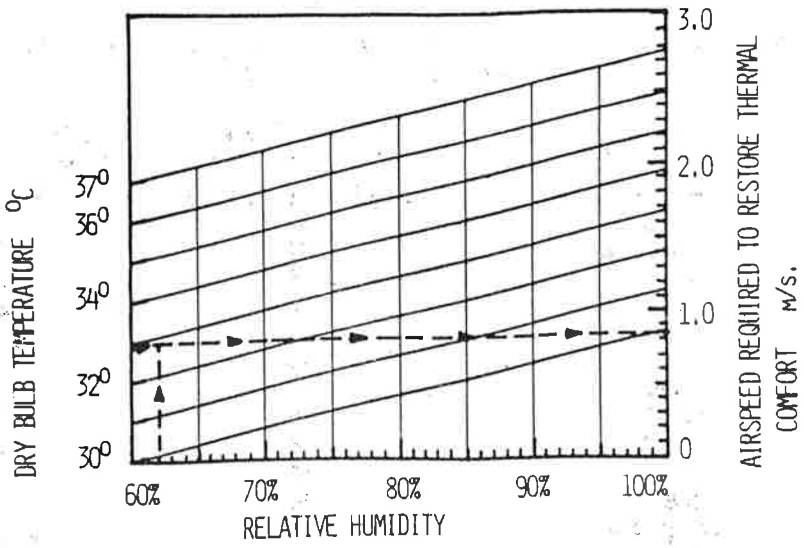


Figure 1. Airspeed required to restore thermal comfort in warm humid environments given dry bulb temperature and relative humidity

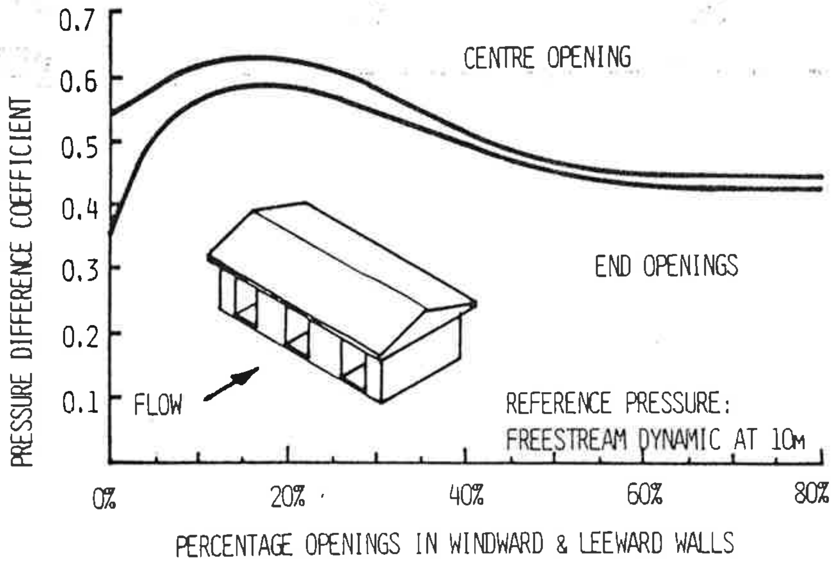


Figure 2. Influence of openings through building on windward total pressure to leeward static pressure difference

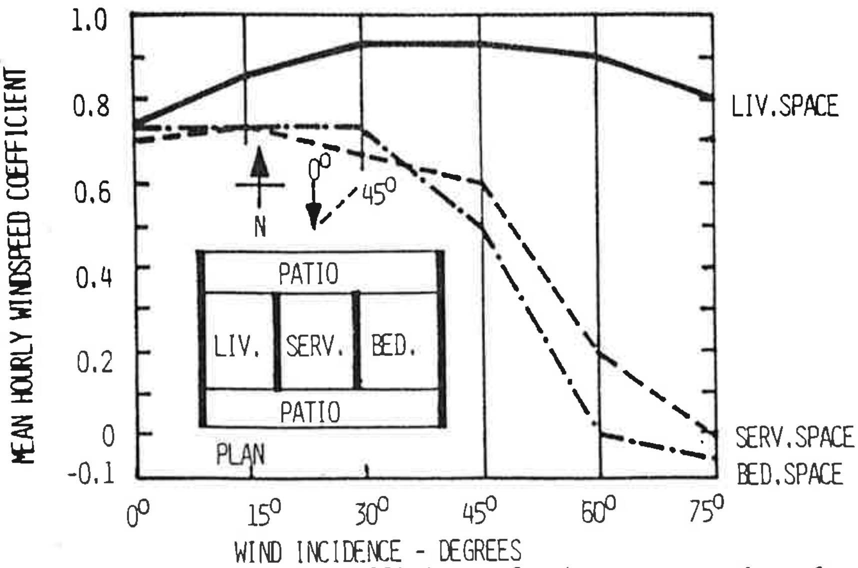


Figure 3. Mean hourly windspeed coefficients for house on-grade referenced to mean freestream windspeed at 10 m