WIND-GENERATED NATURAL VENTILATION OF HOUSING FOR THERMAL COMFORT IN HOT HUMID CLIMATES

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ABSTRACT

This paper investigates a rational method of utilizing recent improvements in wind tunnel techniques and meteorological data, to estimate potential wind-generated airflow through housing in hot humid climates. The method uses mean pressure differences obtained from solid wind tunnel models, together with appropriate discharge coefficients for rectangular openings. Changes in pressure distributions, due to typical openings through models, indicated that the use of pressure data from solid models results in errors similar to those associated with the local wind data. Pressure distribution characteristics are provided for six model types, both isolated and in two parallel rows, for a range of wind incidences.

Orientation of long walls of houses to the north and south is recommended to avoid sun control devices covering wall openings. A simple graph provides estimates of airspeed necessary to restore thermal comfort inside well insulated, and naturally ventilated houses in hot humid climates, using input from readily available climatic data.

INTRODUCTION

Natural ventilation has been a traditional feature of much of the housing built in hot humid tropical regions. Even today many residents in such regions prefer natural ventilation to air conditioning or mechanical ventilation systems which can be expensive to operate and are often difficult to maintain in remote locations. Where mechanical equipment is used there is a preference toward simpler units such as low speed ceiling fans or evaporative coolers (1).

Almost three million square kilometres of the Australian continent, 39%, lie within the tropics, with major cities located in hot humid areas along the coastline. Design of housing in these cities demands careful attention to thermal characteristics of the building envelope, sun control, as well as provision of adequate air conditioning or air movement for comfort.

In contrast with the common use of long-established techniques for estimating thermal characteristics, sun shading and air conditioning loads, there are no established techniques in use for estimating potential natural airflow through tropical housing. This paper investigates rational methods of utilizing recent improvements in wind tunnel techniques and meteorological data, to estimate potential wind-gener-

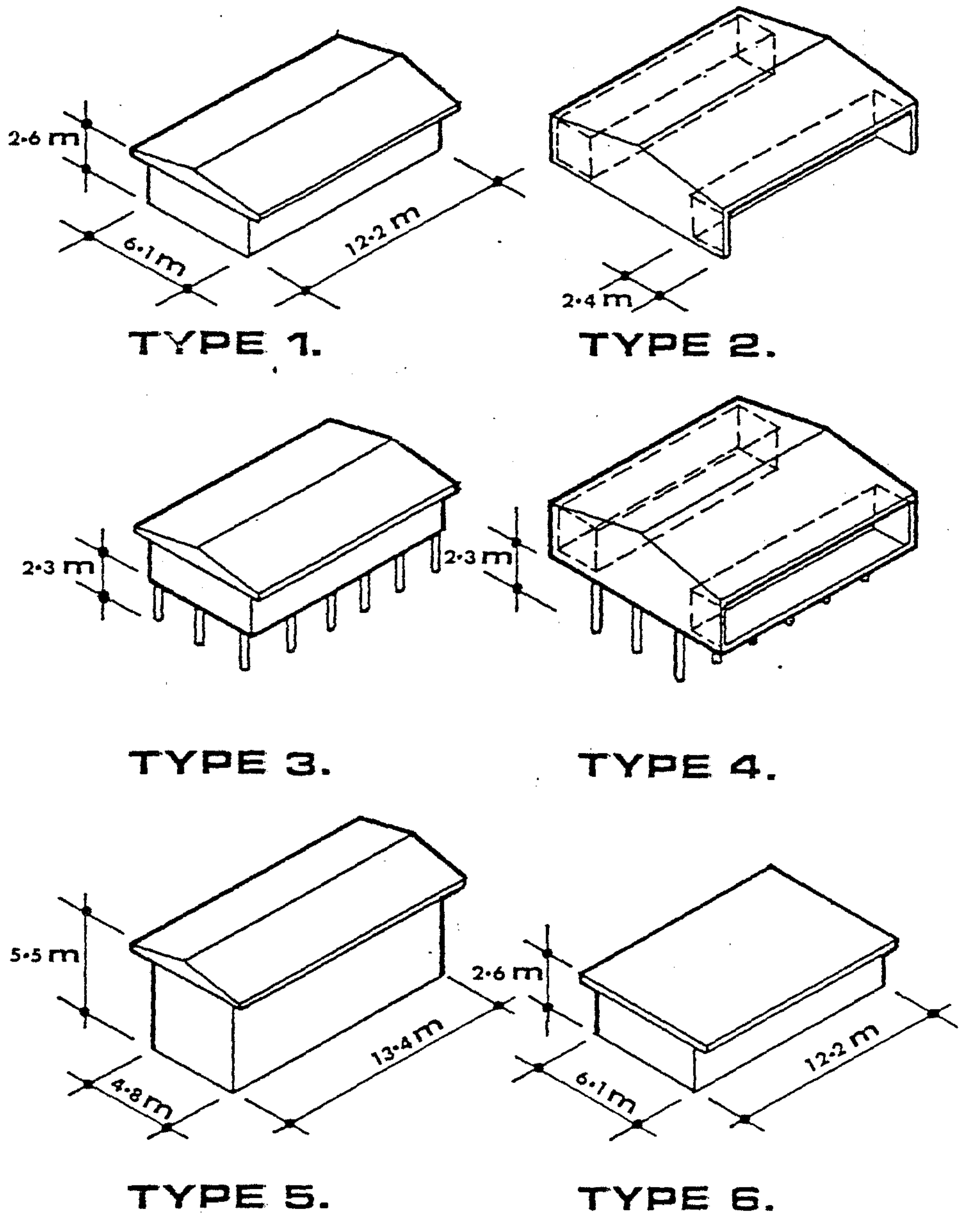


Figure 1. Solid model types used in mid-wall height pressure distribution studies

ated airflow through tropical housing.

Outline of Wind Tunnel Wind Pressure Distribution Studies

Initial wind tunnel studies investigated pressure distributions on the walls of three dimensional solid models both singly and in groups. Six model types were used representing symmetrical housing forms, rectangular in plan, common to Australia's hot humid tropics: single storey on-grade models; elevated single storey models with and without extended eaves and end walls; and, a two storey model. All models had low pitched gable roofs, except one on-grade model which had a flat roof (Fig. 1).

The wind tunnel used was of open circuit blower design with test section 450 mm in width by 300 mm high at its outlet. The lower portion of the mean windspeed profile was modelled with an exponent of 0.28 and a gradient height of 396 metres at a scale of 1 : 150. Maximum model blockage was limited to 2.4% of the test section. Mean windspeed at a height equivalent to 10 metres above ground was 7.8 m/s. All pressure coefficients were referenced to the dynamic pressure upwind of the models at this height to allow direct use of local 10 m meteorological mean windspeed data.

Basis for Pressure Measurements at Mid-Height of Walls

In low, residential buildings most openings for natural ventilation are near the mid-height of walls. A study of the vertical distribution of wind pressure, at a number of points on walls of a range of model buildings, with projecting eaves at various incidences to the wind, indicated wind pressure at a mid-height point on a wall provided a good estimate of the average of wind pressures on a vertical line through that point, over the full height of the wall. Where wind pressures increased near the top of a wall they were generally offset by similar decreases in pressures near the base of the wall. The reduction in the number of measurements achieved by restricting measurements to mid-wall height observations allowed more types and arrangements of models to be studied in the time available.

Influence of Architectural Features on Isolated Solid Model Pressure Distributions

Architectural features such as projecting eaves, projecting end walls and balconies, as well as elevation of single storey buildings raised above ground level, were found to have a significant effect on the magnitude and distribution of wind pressures on wall surfaces of solid, isolated model buildings in wind tunnel tests.

Comparison of average pressure difference coefficients between the mid-height of the long walls on six types of isolated solid model houses with wind at normal, 30° and 45° incidence to a long wall is indicated in Table 1.

Orientation of long walls of houses to the north to minimize solar heat gain and obstruction to airflow by sun control devices at locations along the north Queensland coast, often results in a prevailing summer wind incidence of 45° to a long wall (Fig. 2).

Ranking by average pressure difference coefficient between the long walls of the six model types at 45° wind incidence to a long wall is indicated in Table 2.

Generally the average pressure difference between the long walls of solid isolated models tested (indicating average potential for airflow between long walls) was maximum with wind incidence normal to a long wall. The exception was the single storey on-grade model type 2 with extended eaves and end walls. On this model the average pressure difference coefficient between the long walls was greatest (0.71) with wind at inclined incidence of 30° to a long wall (see Table 1).

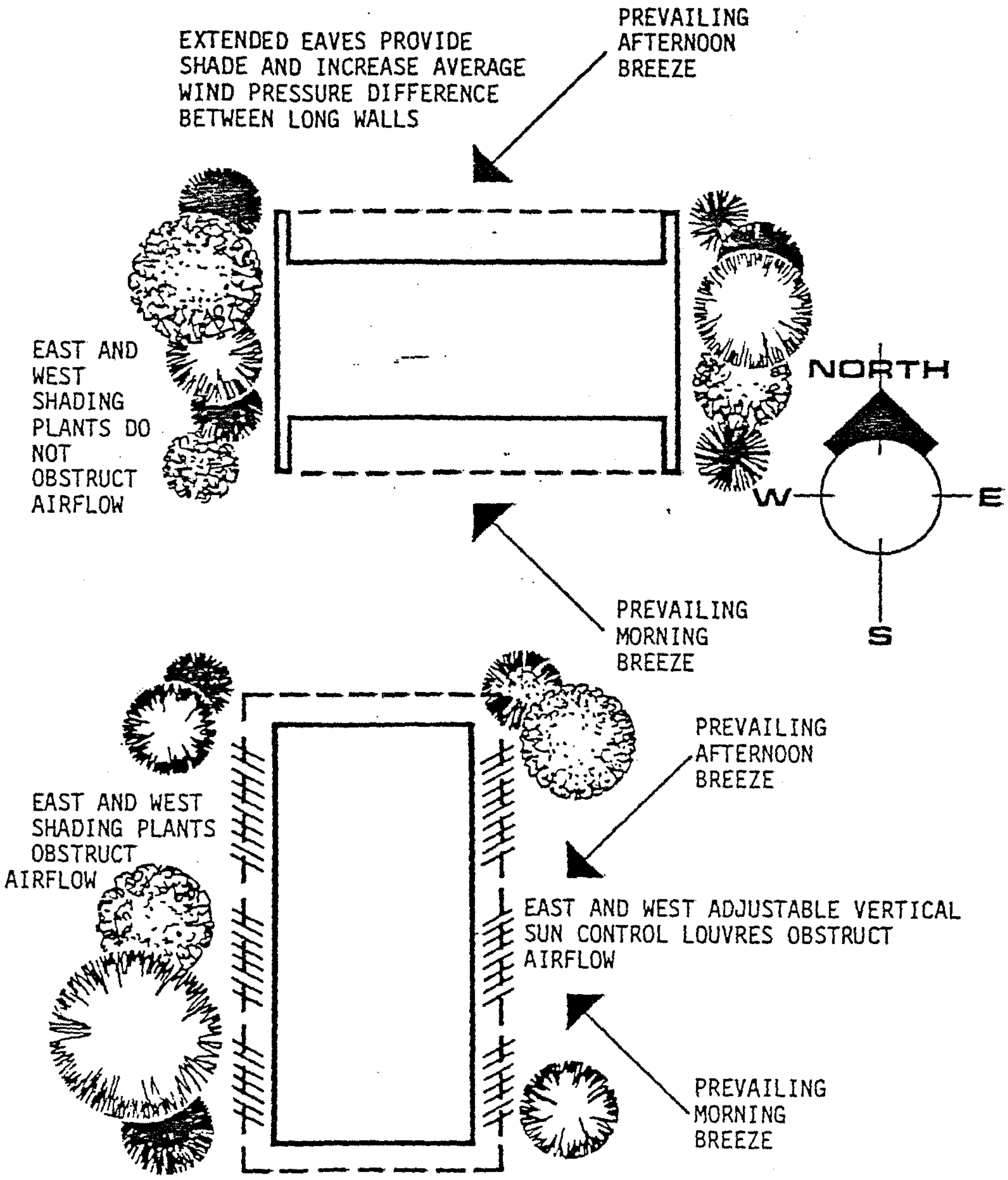


Figure 2. Orientation of long walls to minimise obstruction of openings by shading devices

TABLE 1. Summary of Wind Pressure Difference Characteristics at Mid-Height of Walls on Six Types of Isolated Models at Wind Incidences, Normal, 30° and 45° to Long Walls

Model Features	Model Type	Overall Ranking Based on Average Pressure Diff. Coefft. Between Long Walls	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
Single storey on-grade	1	Worst	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		
Single storey on-grade with extended eaves and end walls	2	2nd best	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		
Single storey elevated above ground	3	3rd best	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		
Single storey elevated above ground with extended verandahs and end walls	4	Best	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		
Two storey	5	5th best	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		
Single storey on-grade with flat roof	6	4th best	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		

C = centre one third of long walls
BE = both ends of long walls
WE = windward ends of long walls
LE = leeward ends of long walls

TABLE 2. Wind at 45^0 Incidence to a Long Wall

Model Features	Average Pressure Diff. Coefft. Between Mid-height of Long Walls for Wind at 45^0 Incidence to a Long Wall (Ref. Press.-Dynamic 10 m above Ground in Wooded Suburban Terrain)
Single storey elevated above ground with extended eaves and end walls (type 4) *	0.75
Single storey on-grade with extended eaves and end walls (type 2) *	0.58
Single storey elevated above ground (type 3) *	0.43
Single storey on-grade with flat roof (type 6)	0.35
Single storey on-grade with 10^0 pitch roof (type 1)	0.34
Two storey (type 5)	0.31

Note that the three highest ranking model types *, 4, 2 and 3 at 45^0 incidence were also highest ranking averaged over wind incidences of 0^0, 30^0 and 45^0.

Maximum pressure difference between opposite points on the long walls of solid isolated models (indicating potential for airflow at a particular location between the long walls) was generally greater at inclined wind incidence than normal incidence to a long wall. The exceptions were the two storey model (type 5) and the single storey elevated above ground with extended verandahs and walls (type 4), on which maximum pressure difference coefficient between opposite points on long walls occurred at wind incidence normal to a long wall.

Influence of Building Groups on Wind Pressure Distributions on Walls

As the principal arrangement of houses in suburban development is in rows along roadways, a series of tests were performed to determine the effects of combinations of downwind and crosswind spacing on pressure distributions. The practice of erecting houses at the minimum legal set back from the street boundary required by local government authorities is the main influence on the establishment of such a pattern. This arrangement together with minimum legal allotment size results in spacings between the rear walls of houses in the order of 30.5 - 36.6 m (100 - 120 ft.). The upwind terrain roughness and its associated mean windspeed profile in the test section accounted for upwind buildings.

Spacings between walls facing the roadway depend on the width of the streets which result in typical wall spacing from 24.4 to 32.3 m (80 - 106 ft.). Spacing of walls parallel to side boundaries depends on the width of allotments and side set backs required by authorities or provision for vehicular access to the rear of the site. Minimum spacing would be 3.0 m (10 ft.) as required by local government regulations with a typical maximum of around 9.1 m (30 ft.).

In practice, crosswind and downwind spacings would be somewhat random. Because of the considerable time required to perform wind tunnel studies, spacings were rationalised to a series of equal downwind and crosswind spacings.

Pressure distribution studies of solid model on-grade or 'low set' type 1, elevated or 'high set' type 3 and two storey type 5, in parallel rows with wind normal to a long wall, with 3.8 m (12.5 ft.) crosswind spacing and 34.3 m (112.5 ft.) downwind spacings similar to typical subdivisions with 20 m (1 chain) width roadways (Table 3), indicated high set and low set models had similar overall average pressure differences in windward and leeward rows.

TABLE 3. Wind Pressure Differences at Normal Incidence

Model Type	Average Pressure Difference Coefft. Between Long Walls of Windward Models	Average Pressure Difference Coefft. Between Long Walls of Leeward Models
Low set (type 1)	0.58	0.45
High set (type 3)	0.60	0.43
Two storey (type 5)	0.68	0.29

These average pressure difference coefficients between the long walls indicate that the average potentials for airflow between long walls on low set models, type 1, and high set models, type 3, were similar in both windward and leeward rows at this typical suburban spacing with wind normal to long walls.

Although the two storey models, type 5, had greater average potential for airflow between long walls than low set and high set model, types 1 and 3, in the windward row, average potential for airflow between long walls on two storey models, type 5, in the leeward row was much lower than corresponding potential on model types 1 and 3.

TABLE 4. Wind Pressure Differences at 30^0 and 45^0 Wind Incidence

Model Type	Crosswind Spacing	Downwind Spacing	Average Pressure Diff. Coefft. Between Mid-height of Long Walls of Windward Models		Average Pressure Diff. Coefft. Between Mid-height of Long Walls of Leeward Models	
			30^0	45^0	30^0	45^0
High Set (type 3)	5.7 m (18.75 ft)	26.7 m (87.5 ft)	0.63	0.53	0.48	0.40
Low Set (type 1)	5.7 m (18.75 ft)	26.7 m (87.5 ft)	0.30	0.20	0.46	0.45
Two Storey (type 5)	7.6 m (25.0 ft)	26.7 m (87.5 ft)	0.38	0.26	0.32	0.29

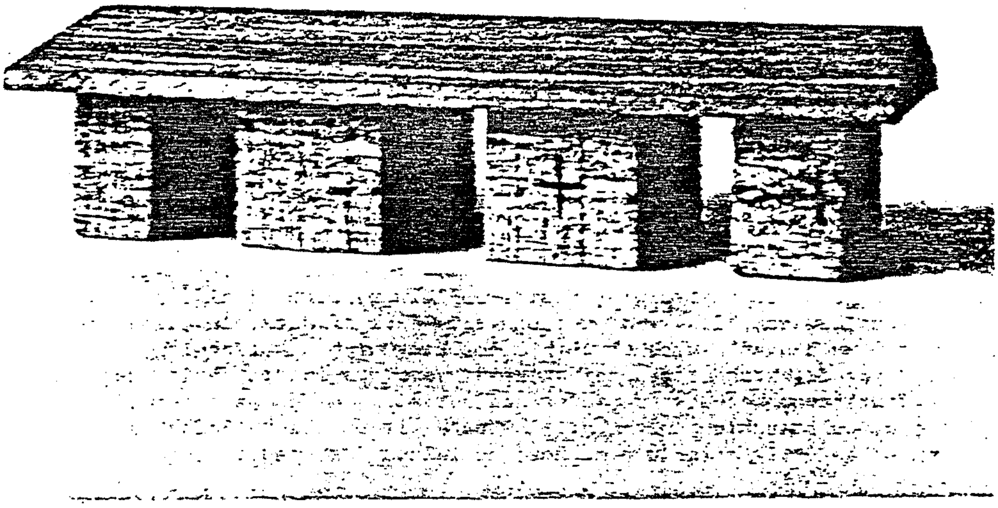


Figure 3. Porous low set model with three equal width channels between long walls centred between pressure measurement point. High set model similar but raised equivalent of 2.3 m above ground.

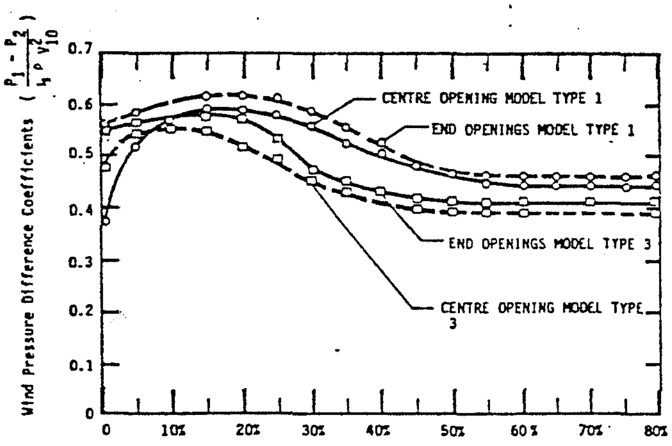


Figure 4. Percentage area of 3 openings between windward and leeward walls

to a long wall, maximum potential for mean windspeed through low set models of the type studied would be achieved with a porosity of 20%, and through high set models with a porosity of 10%.

Estimation of Flow Through Openings

An equation (1) can be written for the mean windspeed V_o through an opening using appropriate discharge coefficients, C_d, from Table 5 and pressure coefficients for total windward pressure C_{p1}, and leeward static pressure C_{p2}, referenced to dynamic pressure of the mean windspeed, V_z (m/s), Z being the height (metres) above ground (usually 10 m) for which long term mean windspeed data is available.

$$V_o = C_d \left[(C_{p1} - C_{p2}) V_z^2\right]^{\frac{1}{2}} \text{ m/s (ft/sec)} \qquad (1)$$

or in terms of volumetric flow rate Q:

$$Q = C_d A \left[(C_{p1} - C_{p2}) V_z^2\right]^{\frac{1}{2}} \text{ m}^3\text{/s (ft}^3\text{/sec)} \qquad (2)$$

These equations for airflow through a single opening in a building due to differences in wind pressure are difficult to apply, as there is little detailed data available on pressure due to wind inside buildings, with significant openings in windward and leeward walls. To overcome this lack of data, in cases where internal airflow follows a simple path through a building without branching, it is convenient to combine the discharge characteristics of each opening in series and use the wind pressure difference between the inlet and outlet openings on external walls. The condition of no branching in the airflow path within the building is not a major restriction, as it is a feature of most buildings designed to encourage natural airflow.

For a number of openings in series

$$Q = \left|\frac{(C_{p1} - C_{p_{n+1}}) v_z^2}{\frac{1}{C_{d_1}{}^2 A_1{}^1} + \frac{1}{C_{d_2}{}^2 A_2{}^2} + \frac{1}{C_{d_3}{}^2 A_3{}^2} + \cdots \frac{1}{C_{d_n}{}^2 A_n{}^2}}\right|^{\frac{1}{2}} \begin{array}{c}\text{m}^3\text{/s} \\ \text{(ft}^3\text{/sec)}\end{array} \qquad (3)$$

The area of openings in windward walls should be reduced by multiplying by a factor equal to the cosine of the angle of wind incidence in the case of inclined wind incidence to openings.

Mean windspeeds through each of the openings is found by dividing the common discharge rate Q by the local opening area A.

Comparison of pressure differences between long walls on solid and porous models at normal incidence, indicated estimates of mean windspeed through buildings using the discharge equation (3) with pressure differences from solid models would be underestimated with porosities up to 20% and would be overestimated with porosities over approximately 35%. An exception to these observations occurred near the ends of the long walls of the low set models. In this case mean windspeed estimates using equation (3) based on solid model pressure differences would be underestimated for porosities between 5% and 80% compared with similar estimates using pressure differences from porous models.

For buildings similar to model types 1 and 3, pressure difference coefficients can be taken from Fig. 4 for appropriate long wall porosities. Further wind tunnel work is planned for other model types and inclined wind incidences.

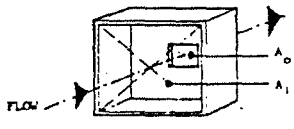
Errors in estimated mean windspeed resulting from the use of pressure differences on solid high set models, being proportional to the square root of the pressure difference, would be +2% to -13% near the ends of the long walls and +7% to -10% near

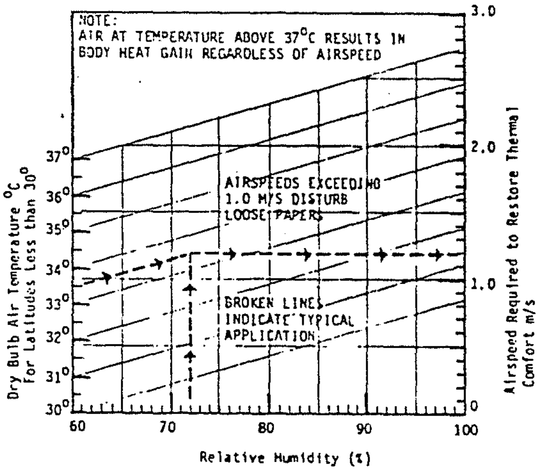
TABLE 5. Typical Discharge Coefficients for Single Inlet or Intermediate Openings in Buildings

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

Typical Discharge Coefficients for Leeward Outlet Openings

A_0/A_1	C_d
Approaching	
0.0	0.63
0.2	0.64
0.4	0.67
0.6	0.71
0.8	0.81
1.0	1.00





Graph for Estimating Minimum Airspeed Required to Restore Thermal Comfort for a Range of Dry Bulb Temperatures and Relative Humidity

Figure 5. Graph for estimating minimum airspeed required to restore thermal comfort for a range of dry bulb temperatures and relative humidity

the centre of the long walls.

When dealing with variables such as estimates of the speed and direction of the natural wind, variations of say 15% must be expected. This would suggest that the use of pressure differences from similar groups of solid models would be of at least the same order of accuracy as short term estimates of local windspeeds and could be justified for estimating airflow through high set houses with wind normal to a long wall.

Estimates of Indoor Thermal Comfort

To estimate the percentage of time that indoor thermal comfort will occur at a particular time of day and month of year, estimates of windspeeds through openings, (using local windspeed, direction and frequency data), relative humidity, 86 percentile daily maximum dry bulb temperature and thermal comfort criteria, such as those suggested by Macfarlane (3) are required. As dry bulb temperatures and relative humidity are relatively constant for each hour of the day during monsoonal months, the writer suggests the percentage of time thermal comfort is achieved will follow directly the percentage of time that airspeeds occur sufficient to restore thermal comfort near wall openings in buildings [examples given in (4)].

Estimates of indoor comfort are limited to 9 am and 3 pm, as these are the only times of day for which reliable, long term, relative humidity and dry bulb air temperature data are readily available in Australia.

A graph (Fig. 5) was developed by the writer to simplify estimation of speed necessary to restore indoor thermal comfort in well shaded and well insulated, naturally ventilated housing in hot humid regions, based on Macfarlane's thermal comfort criteria.

CONCLUSIONS

Architectural features common to housing in Australia's hot humid tropics have significant effects on the wind pressure distributions on wall surfaces and need further study in wind tunnels. Subdivision of land and regulations on building setbacks from boundaries dictate spacing of houses and in turn the wind energy available to naturally ventilate indoor spaces. Pressure differences across houses at normal wind incidence are influenced by the ratio of the area of openings between the windward and leeward walls to the total windward-leeward wall areas. These influences require further study for inclined wind incidences and a wider range of building shapes. Existing wind and climatic data can be used to make preliminary estimates of the likely occurrence of sufficient airflow to restore thermal comfort in naturally ventilated tropical housing.

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