NATURAL VENTILATION MODEL STUDIES

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1.INTRODUCTION

Although natural ventilation has been utilised since antiquity to provide fresh air and indoor air movement for thermal comfort,(Vitruvius, Ref.1), it was not until the 1950s that wind tunnels were used to make quantitative estimates of natural ventilation. Dick (Ref.2) used wind pressure distributions from wind tunnel studies in conjunction with discharge coefficients to estimate natural ventilation through small wall vents and cracks around doors and windows. Smith (Ref.3) measured windspeeds through window openings in a model in a wind tunnel and expressed them as windspeed coefficients referenced to a windspeed outside the model. Both studies incorporated limited full-scale correlation to verify their method.

Later Van Straaten (Ref.4) performed similar studies to those of Dick on windspeeds through large window openings in models of school classrooms. Many of these early studies were performed in uniform flow conditions with no attempt to model boundary layer flow or control blockage effects. Limitations of such studies are discussed by Aynsley (Ref.5) while McKeon (Ref. 6) has studied pressure changes due to high tunnel blockage. Data from these early studies were used to formulate guidelines for design of naturally ventilated houses (Claudill,Ref.7), classrooms (Claudill,Ref.8) and factories (Weston,Ref.9). Little further development took place in techniques for determining quantitative estimates of natural ventilation until the 1970s when rapid advances in boundary layer wind tunnel techniques and full-scale studies of wind characteristics provided opportunities for more detailed design data.

2.ADVANTAGES OF WIND TUNNEL MODELLING FOR ESTIMATING NATURAL VENTILATION OVER THE TRADITIONAL APPROACH.

By taking advantage of developments in boundary layer wind tunnel techniques (Surry, Ref.10), together with refinements in airflow criteria and long term climatic data in probabilistic form (Vickery,Ref.11), a designer can vastly improve on the traditional methods used in estimating natural ventilation.

The traditional methods are described in mechanical engineering reference sources such as A.S.H.R.A.E. (Ref.12) and I.H.V.E. (Ref.13) handbooks. Typically they rely on a simple equation such as:

$$Q = E.A.V \qquad \text{(Equation 1)}$$

where Q is the airflow in cubic metres per second,
E is the efficiency of an opening, ranging from 0.25 to 0.60,
A is the free area of an opening in square metres,
and V is the mean external windspeed in metres per second.

A range of correction factors are often applied for conditions which are known to grossly effect the estimate. Such an approach cannot

From: Wind Tunnel Modeling for Civil Engineering Applications. Ed: T.A. Reinhold CUP, 1982.
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effectively account for:

1. Physical structure of wind at a particular site in terms of mean windspeed profile or turbulence characteristics.
2. Influence on local wind due to nearby obstructions, topographic features or vegetation.
3. Influence of architectural features such as extended eaves, sun-screen devices or wall projections on airflow around a building.
4. Influence of size, proportion and location of openings in a building on airflow pattern.

Model studies in boundary layer wind tunnels provide a means of investigating all these influences for a particular site and building design. Most boundary layer wind tunnel techniques have been shown to be sufficiently accurate for most design purposes (Vickery,Ref.11, Dalgleish,Ref.14 and Isyumov,Ref.15) and are continually being refined. Some wind tunnel techniques for determining influences such as vegetation on local winds (White,Ref.16) need further correlation of model and full-scale studies to determine their order of accuracy.

3.STRATEGIES FOR UTILISING NATURAL VENTILATION IN BUILDINGS

There are two strategies for utilising natural ventilation. One assumes primary reliance on natural ventilation with use of fans only during periods of calm (Aynsley,Ref.5). The other strategy assumes reliance on a mechanical ventilation or air conditioning system, primarily, with the possibility for natural ventilation by providing openable windows and doors in the event of systems breakdowns or interruptions to power supplies. This is being promoted by the governments of Singapore and Papua New Guinea (Ref.17 and 18). In this case natural ventilation is a substitute for an on-site generator system. In either case power failures do occur, standby generators can fail and winds can cease to blow.

Any rational system for assessing these strategies should involve the determination of "acceptable risk" in terms of loss of acceptable indoor environmental conditions. This amounts to estimating the probability of the occurrence of an "unacceptable event" and the consequences of that event. Obviously to make such an evaluation, long term climatic data on temperature, humidity and wind is needed in probabilistic form so that an estimate of the likely frequency and duration of unacceptable environmental conditions can be made.

"Unacceptable events" in terms of indoor environmental conditions may be determined from thermal comfort criteria (Givoni,Ref.19), temperature or humidity limits for storage or processing of goods, or operation of equipment, or fresh air requirements for each indoor space.

"Consequences of events" can be evaluated in terms such as; loss of thermal comfort, monetary cost, loss of production, ongoing viability of a business enterprise, or the need to relocate site of operations.

4.CURRENT APPROACHES TO ESTIMATING NATURAL VENTILATION

In recent years studies of natural ventilation in buildings have taken two distinct paths. One path pursuing "infiltration" through small cracks and openings associated with heat loss problems or build-up of indoor pollutants in cold climates. This path has concentrated on full-scale measurements using pressurised buildings and tracer gas decay or replenishment techniques, together with the development of mathematical models for computing infiltration rates for typical building types. Research in this area is being co-ordinated by the Air Infiltration Centre, Bracknell in Great Britain.

Natural ventilation studies of flow through larger openings for indoor thermal comfort in warm climates have taken two paths. One approach uses windspeed coefficients measured in boundary layer wind tunnels in conjunction with thermal comfort criteria and climatic and wind frequency data.

The other approach makes use of existing published wind pressure distribution and discharge coefficient data in conjunction with thermal comfort criteria and climatic and wind frequency data.

5.ESTIMATING NATURAL VENTILATION USING MEAN WINDSPEED COEFFICIENT METHODS.

A useful method of quantifying natural airflow inside buildings suggested by the writer, Aynsley (Ref.20) for the design of buildings in hot humid climates involves the use of windspeed coefficients. These coefficients, C_v, are the ratio of the mean windspeed, $\overline{V}_1$, at a point of interest indoors, usually one metre above floor level, to the mean windspeed, $\overline{V}_z$, at a specified reference height, z, usually 10 m, upstream from the building in the airflow undisturbed by the building (Fig.1) so that:

$$C_{\overline{v}_1} = \frac{\overline{V}_1}{\overline{V}_z} \qquad \text{(Equation 2)}$$

Given the variation in individual's response associated with thermal comfort criteria and the limited availability of detailed temperature, humidity and windspeed data, a one hour meaning period for windspeed data seems reasonable to the writer for thermal comfort estimates.

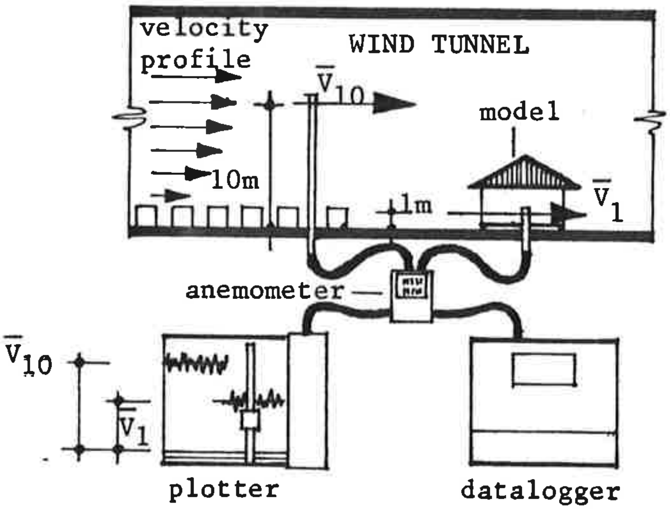


Figure 1:
Wind Tunnel Technique
for Determining Mean
Windspeed Coefficients

$$C_{\overline{v}_1} = \frac{\overline{V}_1}{\overline{V}_{10}}$$

By adopting a common reference windspeed in similarly modelled winds, ventilation windspeeds can be directly compared from a range of different building models. When wind frequency data for mean 10 metre windspeeds ($\bar{V}_{10}$) and wind directions near the building site are available for a particular month and time of the day, airspeed V_1, through the full-scale building can be estimated. Using the appropriate mean windspeed coefficient $C_{\bar{V}_1}$ from a wind tunnel study, with the model orientated at the corresponding wind direction:

$$\bar{V}_1 \text{(full-scale)} = C_{\bar{v}_1} \cdot \bar{V}_{10} \text{ (full-scale)} \qquad \text{(Equation 3)}$$

Some mean windspeed coefficients determined from a simple model by the writer for windspeeds 1 m above floor level and related to 10 m reference windspeeds for buildings subdivided by solid partitions (Fig.2), are indicated in Figure 3.

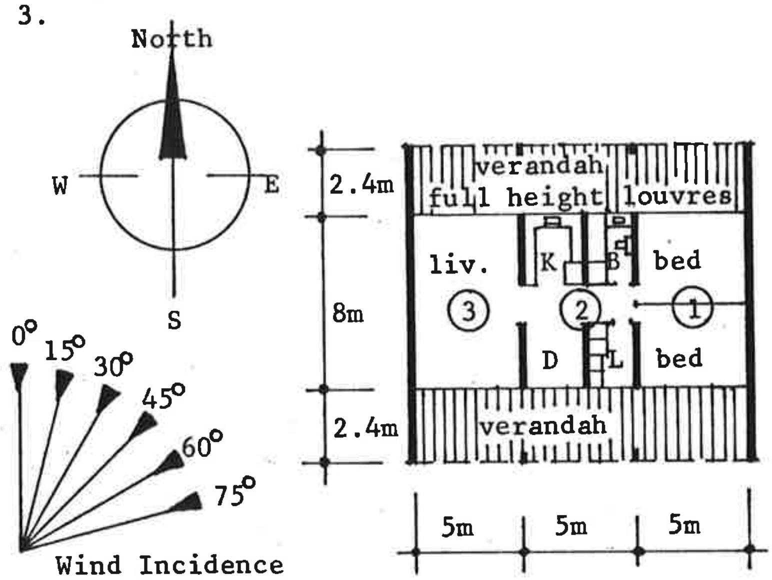


Figure 2: Floor Plan.

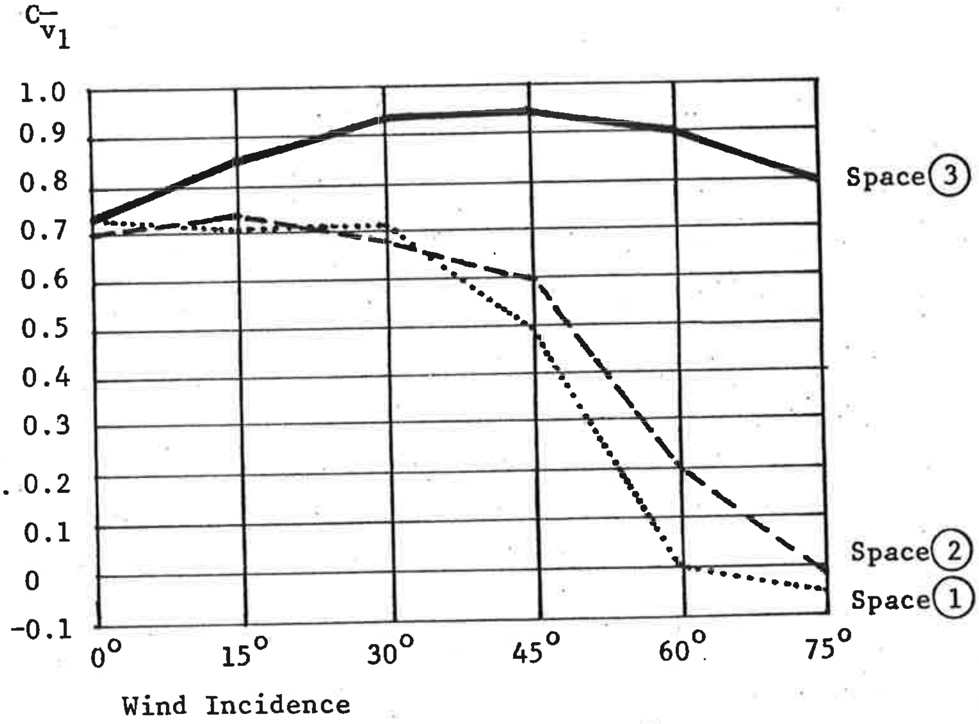


Figure 3: Mean Windspeed Coefficients for Spaces in Model in Fig.2 Reference Windspeed 10m with a Mean Windspeed Profile Exponent of 0.28 and a Gradient Height of 400m.

Windspeed coefficients in industrial buildings were studied by Weston (Ref.9) in the wind tunnel at the Commonwealth Experimental Building Station in Australia during 1954. Further wind tunnel studies by Van Straaten (Ref.21) of school classrooms provided additional windspeed coefficient data. More recent sources of windspeed coefficients for housing come from studies by Givoni (Ref.22) and Chand (Ref.23).

These windspeed coefficients were based on low level external reference windspeeds, and tests were conducted in uniform airstreams,which makes estimation of actual prototype velocities from the meteorological wind data difficult. Hamilton (Ref.24) showed the effect of velocity profile on wind pressures on low buildings. The writer's method stresses the need for the reference windspeed to be measured in an appropriate mean windspeed profile at a height for which detailed long term wind data is available.

A similar technique,described by Vickery and Apperley (Ref.11) for predicting the probable frequency of strong wind gusts near ground level in urban terrain, was found to have an accuracy in the order of plus or minus 10%. With careful modelling, similar accuracy should be possible in estimates of indoor windspeeds.

The windspeed 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 windspeed coefficients directly.

A typical natural ventilation study in this category was performed by the writer in the Department of Architectural Science's wind tunnel at the University of Sydney. The building was a large single storey building designed for a location in the central Pacific (Fig.4). Most external walls consisted of floor to ceiling sliding screens and extensive use was made of quadrant-shaped ventilation hoods fixed at various locations on the roof. The design also incorporated a number of courtyard areas within the building to which wall openings were provided. Windspeeds inside this model at a height equivalent to 1 metre above floor and externally at a 10 metre reference height were measured with a 'Davimeter' thermocouple type anemometer. Output from the anemometer was recorded using an X-Y plotter on paper calibrated to the anemometer response.

The principal advantage of the windspeed coefficient approach is that mean windspeed 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 which deflect the airstream, such as louvres or tilting sashes, need to be modelled 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 windspeed coefficients restricts its application for many small buildings. Most studies on low cost buildings have been made in research programmes at government research stations and at universities.

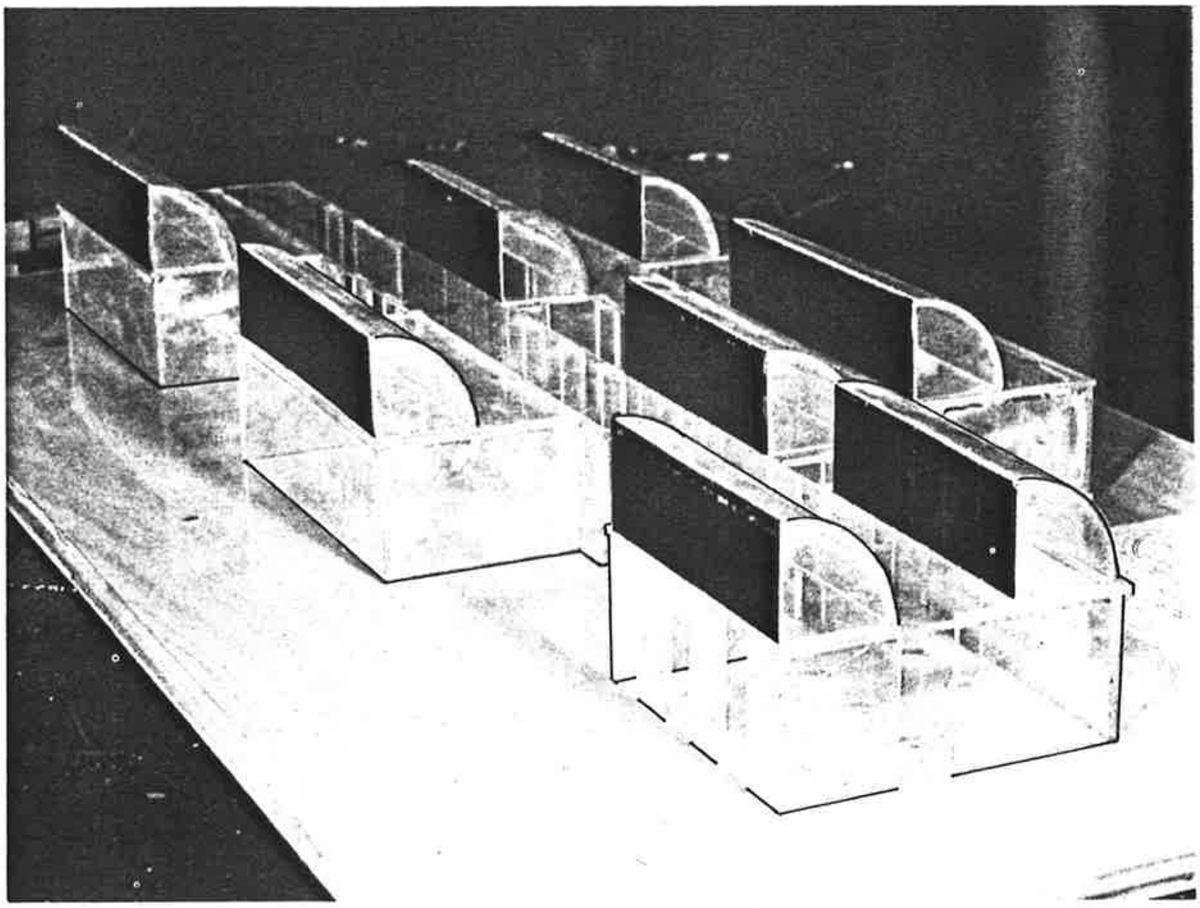


Figure 4: Wind Tunnel Model used to Study the Effectiveness of Natural Ventilation Scoops Incorporated in Roof Form.

The full-scale effects of insect screens or other wall components with curved or rounded sections in the airflow cannot be assessed on wind tunnel building models. Even if insect screening could be reproduced accurately at small scale, flow past rounded elements in insect screening, for example, could be significantly different due to differences in Reynolds numbers of the flow at full and model scale.

For these reasons, unless components installed in wall openings are composed of sharp-edged, flat surfaced shapes and can be accurately modelled at small scale, openings in models should be kept clear. A windspeed reduction factor, established from full-scale studies of wall components, can then be applied to the flow through clear openings in the model to allow for the effect of inserting components such as insect screens. Typical windspeed reductions due to insect screens are indicated in Table 1.

Screen Material	Windspeed through clear opening m/s	% Windspeed reduction with screen %
Bronze wire screen, 5.5 wires/cm, porosity 80%	2	26
	4	17
	6	11
Plastic-coated fibreglass, 7 threads/cm, porosity 60%	2	41
	4	34
	6	19

Table 1: Windspeed Reductions through Screens.

5.1 Estimating Indoor Thermal Comfort from Natural Ventilation using Mean Windspeed Coefficients

By combining estimates of airflow through openings with the frequency of occurrence and direction of winds, relative humidity, dry bulb temperature and thermal comfort criteria by Macfarlane (Ref.25), the writer estimates the frequency of occurrence of windspeeds sufficient to restore thermal comfort in buildings. Estimates and indoor comfort are generally limited to 9 am and 3 pm as these are the only times for which simultaneous long term windspeed, relative humidity and 86 percentile dry bulb air temperature data for each month are readily available in Australia (Ref.26 and 27).

Determination of windspeed necessary to restore indoor thermal comfort in well shaded insulated and naturally ventilated housing in hot humid regions, based on Macfarlane's method, can thus be quickly assessed using Figure 5 developed by the writer. An example of such a calculation is provided in Appendix 1 to this paper.

5.2 Summary of Advantages and Disadvantages of the Mean Windspeed Coefficient Method.

Advantages:

1. Simplicity of the method, only reference and indoor mean windspeeds at points of interest are measured,
2. Windspeed coefficients can be obtained at any point inside a model where an anemometer can be placed, in main airstream as well as eddy zones.

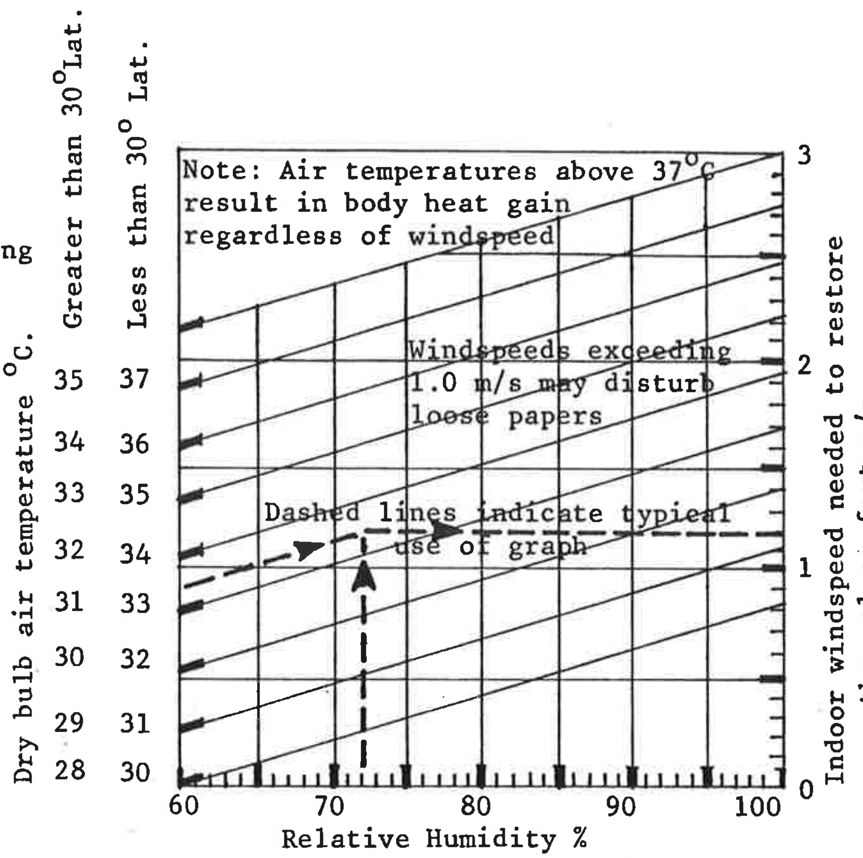


Figure 5:

Graph for estimating indoor windspeed needed to restore thermal comfort assuming insulation is provided to eliminate radiant heat gain to occupants.

Disadvantages:

1. Designers need access to boundary layer wind tunnel test facilities.
2. Need for extremely accurate modelling of openings where inclined sashes or louvres are involved.

6. WIND DISCHARGE COEFFICIENT METHOD

The attraction of a discharge coefficient method is that the increasing amounts of pressure distribution data from boundary layer wind tunnel studies for wind loading and discharge coefficients used in design of ventilation ducts, offer a means of estimating natural ventilation in a design office without resorting to special wind tunnel studies.

Obviously using pressure coefficients or discharge coefficient data derived for ventilation ducts or wind loadings to improvise estimates in another application is not an ideal approach. However limited sources of discharge coefficients derived from natural ventilation studies do not account for smaller contraction of flow at entries of openings in buildings when flow can divide around the building.

With regard to pressure distributions used in wind loading applications they are usually derived from models without openings. Typical differences between pressure differences across models with and without openings have been measured, (Aynsley, Ref.28). However if a particular building does not warrant the expense of a special wind tunnel study, the approximate methods such as discharge coefficient approach may be justified as an improvement over traditional methods for estimating natural ventilation such as Equation 1.

6.1 Estimation of Flow Through Openings using Discharge Coefficients

An equation (4) can be written for the mean windspeed $\overline{V}_0$ through an opening using appropriate discharge coefficients, C_d, from Tables 2 or 3 and pressure coefficients for total windward pressure C_{p1}, and leeward static pressure C_{p2}, referenced to dynamic pressure of the mean windspeed $\overline{V}_z$ m/s, z being the height in metres above ground (usually 10 m) for which long term mean windspeed data is available.

$$\overline{V}_0 = C_d\left[(C_{p1} - C_{p2})\,\overline{V}_z^{\,2}\right]^{\frac{1}{2}} \quad \text{m/s} \qquad \text{(Equation 4)}$$

or in volumetric flow rate Q where A is the area of the opening (m^2)

$$Q = C_d A\left[(C_{p_1} - C_{p_2})\,\overline{V}_z^{\,2}\right]^{\frac{1}{2}} \quad m^3/s \qquad \text{(Equation 5)}$$

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 (Figure 6), 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.

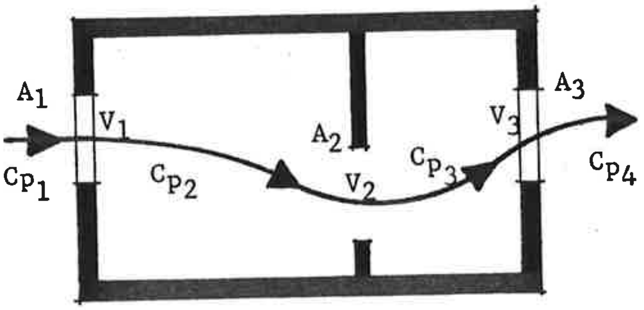


Figure 6:
Typical Wind Flow through Building Openings in Series indicating Terms for Areas of Openings, A, Local Windspeeds, V, and Pressure Coefficients C_p.

For a number of openings in series:

$$Q = \left(\frac{(C_{P_1} - C_{P(n+1)})\, V_z^{\,2}}{\frac{1}{C_{d_1}^{\,2} A_1^{\,2}} + \frac{1}{C_{d_2}^{\,2} A_2^{\,2}} + \frac{1}{C_{d_3}^{\,2} A_3^{\,2}} + \cdots \frac{1}{C_{d_n}^{\,2} A_n^{\,2}}} \right)^{\frac{1}{2}} \quad m^3/s$$

(Equation 6)

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

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

6.2 Estimating Indoor Thermal Comfort from Natural Ventilation using Discharge Coefficients

Volumetric discharge necessary for thermal comfort through each opening can be calculated for each wind direction. This discharge is substituted into the discharge equation to determine the 10 m windspeed necessary for comfort at each opening. The frequency of occurrence for each 10 m windspeed interval exceeding that needed for comfort for a particular wind direction are summed. Repeating this process for each wind direction and totalling all percentages of occurrence indicates the total percentage of time when natural ventilation is likely to restore thermal comfort near the openings under study. An example calculation is provided in Appendix 2 of this paper.

6.3 Sources of Discharge Coefficients for Estimating Natural Ventilation.

Most discharge coefficients found in texts on fluid mechanics are for single, square-edged, round openings in flat plates, or a range of standard orifice designs used for flow measurement in pipes.

Full-scale studies by Dick (Ref.2) in 1950 established that discharge coefficients of approximately 0.65 were appropriate for very small square edged cracks and openings in houses. A.S.H.R.A.E. Guide (Ref.12) contains a wide range of both discharge coefficients and dynamic loss coefficients for rectangular ventilation ducts. Discharge coefficients for larger window openings in series were determined by Wannenburg and Van Straaten (Ref.4) in 1957 for estimating airflow for comfort in school classrooms. These window openings occupied approximately 10% of the wall area. Snyckers (Ref.29) extended the range of discharge coefficients for a range of rectangular openings in series up to 20% of wall area. Airflow rates through openings in series estimated using discharge coefficients from Tables 2 and 3 were found to be within 15% of measured values in a series of wind tunnel studies on a variety of opening geometries and sequences in which openings did not exceed 10% of the wall area (Aynsley, Ref.5). Cosine corrections were made to areas of windward openings in these studies for wind directions not normal to the windward wall.

Description of opening	Typical range of discharge coefficients 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

Table 2: Typical Discharge Coefficients for Single Inlet or Intermediate Openings in Buildings.

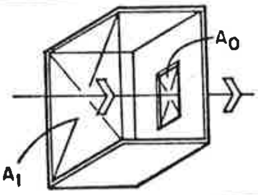
A_0/A_1	C_d	
Approaching 0·0	0·63	
0·2	0·64	
0·4	0·67	
0·6	0·71	
0·8	0·81	
1·0	1·00	

Table 3: Discharge coefficients for Outlet Openings.

6.4 Sources of Pressure Coefficient Data for Estimating Natural Ventilation

There are two major sources of pressure distribution data for building forms, those of Chien, and those of Jensen and Franck. Models used by Chien (Ref.30) in pressure distribution studies were simple block forms with none of the architectural features common to many buildings. Studies by Jensen and Franck (Ref.31) included some models with projecting eaves. Less detailed average pressure coefficients for a range of building forms are provided in wind loading codes (Ref.32). Significant eaves projections are a common sun control feature on low buildings in warm humid climates. Proportions of such architectural features become very significant on smaller buildings and a common practice of raising the building off the ground can cause appreciable changes in pressure distributions (Best, Ref.33).

Pressure distributions at mid-height of walls on recent housing forms built in Australia's hot humid tropics are provided in graphical form by Aynsley (Ref.5) for a number of wind incidences to a long wall.

Most pressure distributions on buildings are determined from wind tunnel studies of isolated models. Where a particular building has other buildings or obstructions nearby accurate pressure distributions can only be obtained by modelling such obstructions during the wind tunnel study. In the case of groups of buildings some studies were performed by Aynsley (Ref.28) and Holmes (Ref.34).

6.5 Advantages and Disadvantages of the Discharge Coefficient Method

Advantages

1. Ability to make use of increasing sources of wind pressure distribution data from wind load research.
2. Approximate estimates of windspeeds through openings can be made without resorting to specific wind tunnel tests by using existing data for building with wall openings less than 20% of wall area.

Disadvantages

1. When building openings exceed 20% of wall area wind pressure differences vary significantly from building forms without openings.
2. Estimates of mean windspeed are restricted to locations in jets close to wall openings, a significant disadvantage when the majority of occupied space is located away from openings.

7. MODELS FOR NATURAL VENTILATION STUDIES

The writer's selection of a scale for a wind tunnel model for measuring windspeed coefficients is governed by:

1. Maximum acceptable tunnel blockage usually 2% of tunnel cross-section for any single building.
2. The ability to be able to reproduce suitable wind characteristics at that scale. For mean windspeed measurements inside buildings a well modelled mean windspeed profile is the principal requirement as long as models are sharp-edged, flat surfaced bluff bodies.
3. The ability to place the anemometer probe inside the model at points of interest without causing more blockage than would be caused by the equivalent of an adult person. This is affected by the size and types of probes available.

In the case of mean pressure distributions studies on solid models, model scale is governed by the factors outlined in 1 and 2 above.

8.WINDSPEED AND WIND PRESSURE MEASUREMENTS

As indoor airflows are often turbulent and undergo frequent changes in direction it is best to use an anemometer probe with a response that is not sensitive to flow direction such as Disa's spherical film probe or Thermo Systems miniature cylindrical film probe. Alternatively a typical miniature hot wire probe can be orientated so as to ensure that the principal changes in flow direction occur around the circumference of the wire and not its length. Where airflow studies are performed to investigate thermal comfort it should be remembered that thermal comfort indices refer only to airspeed and not direction so it is not necessary to record flow direction. However flow visualisation using a short tuft on the end of a wire probe is useful for aligning directionally sensitive anemometer probes with the flow direction.

Where wind pressure tappings on surfaces of small solid models are being measured using a multitube manometer data can be rapidly recorded for each wind direction by photographing the manometer. When data logging facilities are available, measurements are made with a suitable pressure transducer via a scanning valve.

9.NEED FOR FURTHER MODEL AND FULL-SCALE CORRELATION STUDIES

While the correlation studies of natural ventilation estimates from wind tunnel models and full-scale measurements has been encouraging to date (Dick, Ref.2, and Smith, Ref.3) there will need to be many more. Techniques for modelling vegetation to reproduce full-scale flow characteristics need attention as well as proving the reliability of 10 m scaled windspeed measurements in tunnels as a reference for calculating windspeed and pressure coefficients. Where the local 10 m recording anemometer is too distant to include in the wind tunnel model,a smaller scale terrain model can be used to determine direction and windspeed corrections to existing records needed for a substitute reference anemometer location within the perimeter of the model including the building under test (Holmes,Ref.35). Correlation studies will need to be studied in a variety of terrain. The time alone needed for full-scale measurements as well as long term access to suitable test buildings prevents many studies of this nature being undertaken.

10. NEED FOR PRELIMINARY WIND TUNNEL STUDIES IN BUILDING DESIGN

As the size, shape and relative location of a building to adjacent buildings and obstructions are prime influences on the characteristics of airflow around a building, it is essential that these influences be studied in the early stages of the design of a building. It is only during these stages that fundamental changes that may be necessary can be made without suffering a severe cost penalty.

By using small scale clear plastic models together with foam plastic beads as a flow visualisation media, an experienced wind tunnel user can easily locate areas with poor natural ventilation and suggests modification for improvement. Such studies are inexpensive and can help the tunnel user select anemometer probe location points for later quantitative studies.

11. CONCLUSIONS

Use of boundary layer wind tunnel model studies to estimate natural ventilation in buildings appears very promising, particularly windspeed coefficient methods. The mean windspeed coefficient approach to estimating airflow through buildings for thermal comfort seems to offer a number of attractions to architects and other building designers.

Firstly the frequent use of models by architects during the design of buildings suggests that, if the scale was determined so as to meet blockage criteria for an available wind tunnel, a simple series of tests could provide valuable design data.

Secondly the increasing number of boundary layer wind tunnels at universities and building research establishments,suitable for studies of building models,means they are available to many designers at reasonable cost.

Thirdly, the method, when based on readily available meteorological data, provides a simple rational basis for evaluating the relative performance of alternative designs for low-energy, naturally ventilated buildings in oppressive hot humid climates.

Early correlation studies of model and full-scale data show close agreement. However the extreme complexity of wake flows from groups of bluff bodies in a turbulent layer suggests many more such studies will be needed before the reliability and order of accuracy of current modelling techniques can be confirmed.

REFERENCES

1 Vitruvius, The ten books of architecture, translated by Morris Hickey Morgan, Dover, New York(1960).

2 J.B.Dick, The fundamentals of natural ventilation of houses,J.Institution of Heating and Ventilating Engineers, 18,no.2 (1950).

3 E.G.Smith, The feasibility of using models for predetermining natural ventilation, Texas Engineering Experiment Station,Res.Rept.26 (1951).

4 J.J.Wannenburg and J.F.Van Straaten, Wind tunnel tests on scale model buildings as a means for studying ventilation and allied problems, J.Institution of Heating and Ventilating Engineers, (March 1957).

5 R.M.Aynsley,W.Melbourne and B.J.Vickery,Architectural aerodynamics, Applied Science, London (1977).

6 R.J.McKeon and W.H.Melbourne, Wind tunnel blockage effects and drag on bluff bodies in a rough wall boundary layer, Paper from Proceedings of the Third Int.Conf.on Wind Effects on Buildings and Structures (Tokyo), Saikon Shuppan Co.Ltd (1971).

7 W.Caudill, Some general considerations in the natural ventilation of buildings, Texas Engineering Experiment Station, Res.Rept.22 (1951).

8 W.Caudill and Bob H.Reed, Geometry of classrooms as related to natural lighting and natural ventilation, Texas Engineering Experiment Station Res.Rept.36 (1952).

9 E.T.Weston,Natural ventilation in industrial-type buildings, Commonwealth Experimental Building Station, Spec.Rept.14 (1954).

10 D.Surry and N.Isyumov, Model studies of wind effects - a perspective on the problems of experimental techniques and instrumentation, Int.Congress on Instrumentation in Aerospace Simulation Facilities, Record (1975) 76-91.

11 B.J.Vickery and L.W.Apperley, On the prediction and evaluation of the ground wind environment, Dept.of Civil Engineering,University of Sydney Res.Rept.R277 (1973).

12 A.S.H.R.A.E., Handbook of fundamentals, American Society for Heating, Refrigerating and Air-Conditioning Engineers (New York) (1981) Ch.14.

13 I.H.V.E.,Guide, Institute of Heating and Ventilating Engineers (Lond.) (1972).

14 W.A.Dalgleish, Comparison of model/full-scale wind pressures on a high rise building, J.Ind.Aerodynamics, 1,no.1 (1975).

15 N.Isyumov and A.G.Davenport, Comparison of full scale and wind tunnel windspeed measurements in the Commerce Court Plaza, J.Ind.Aerodynamics, 1 (1975) 201-212.

16 R.F.White,Effects of landscape development on the natural ventilation of buildings and their adjacent areas, Texas Engineering Experiment Station, Res.Rept.45 (1954).

17 T.Wheeler, An energy conservation in buildings programme for P.N.G., Energy Planning Unit,Department of Minerals and Energy (Konedobu, P.N.G.) Report 2/81 (1981).

18 R.Stedman, Kent Ridge teaching hospital,Singapore, Institution of Engineers Australia,Nat.Symposium on Energy Conservation in Buildings, (Sydney),(1978) 70-74.

19 B.Givoni,Man,climate and Architecture,2nd ed, Applied Science,London (1976).

20 R.M.Aynsley, Tropical housing comfort by natural airflow, Building Res. and Practice 8,no.4,(1980) 242-253.

21 J.F.Van Straaten,Thermal performance of buildings, Elsevier,Amsterdam, (1967).

22 B.Givoni, Study of ventilation problems in housing in hot countries, Technion,Building Research Station ,Report (Oct.1962).

23 I.Chand, Prediction of air movement in buildings,Central Building Res. Institute (Roorkee) Building Digest 100 (Sept.1972).

24 G.F.Hamilton,Effect of velocity distribution on wind loads on walls and low buildings, University of Toronto,Technical Paper 6205 (Nov. 1962).

25 W.V.Macfarlane, Thermal comfort zones, Architectural Science Review, 1,no.1 (1958) 1-14.

26 Climatic averages Australia, Metric ed., Bureau of Meteorology,Canberra (1975).

27 Wind frequency analyses: computer output for individual locations. Available for purchase from the Bureau of Meteorology,Melbourne.

28 R.M.Aynsley, Wind generated natural ventilation of housing for thermal comfort in hot humid climates, Fifth Int.Conf.on Wind Engineering, July 1979, Colorado State Univ.(Fort Collins) ,Vol.1 (1979) III-3-1 - III-3-12.

29 W.A.Snyckers, Wind tunnel studies of the flow of air through rectangular openings with application to natural ventilation in buildings, University of Pretoria, Master of Science in Engineering Thesis(1970).

30 Ning Chien et al, Wind-tunnel studies of pressure distribution on elementary building forms, Iowa Inst.of Hydraulic Res.,State Univ. of Iowa (1951).

31 M.Jensen and N.Franck,Model-scale tests in turbulent wind,Part II Phenomena dependent of the velocity pressure.Wind loads on buildings, Danish Technical Press,Copenhagen (1965).

32 S.A.A.loading code Part 2 wind forces, Australian Standard 1170,Part 2 (1975).

33 R.J.Best and J.D.Holmes, Model study of wind pressures on an isolated single-storey house, James Cook University,Dept.of Civil and Systems Engineering, Wind Engineering Rept. 3/78 (1978).

34 J.D.Holmes and R.J.Best, A wind tunnel study of wind pressures on grouped tropical houses, James Cook Univ.(Townsville) Dept.of Civil and Systems Engineering,Wind Engineering Report 5/79 (1979).
35 J.D.Holmes, G.R.Walker and W.E.Steen, The effect of an isolated hill on wind velocities near ground level - initial measurements, James Cook University (Townsville), Dept.of Civil and Systems Engineering Wind Engineering Report 3/79 (1979).

APPENDIX 1.

Example

Determine the likelihood of maintaining comfort by natural airflow in the living area of a low set residence with extended eaves and end walls (Fig.2) in Townsville at 3 pm during January.

Climatic Data

3 pm, 86 percentile daily maximum dry bulb temperature for January = $32.9^{\circ}C$

3 pm average relative humidity = 62%

Airflow needed to restore comfort from Figure 5 = 0.83 m/s

Mean Windspeed Coefficients

Method : Using mean windspeed coefficient $C_{\bar{V}_1}$ of 0.72 for the living room indicated in Figure 3 for wind from the North, the windspeed, $\bar{V}_{10}$ 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 windspeed $\bar{V}_1$,

$$\bar{V}_{10}\text{(for comfort)} = \frac{0.83}{C_{\bar{V}_1}} \qquad \text{from Equation 3}$$

$$= \frac{0.83}{0.72}$$

$$= 1.15 \text{ m/s}$$

By summing the frequency of occurrence of all windspeeds 1C metres above the ground, from Table 4, which exceed 1.15 m/s for winds from the North, an estimate of the percentage of time winds from the North would provide thermal comfort in the living room, at 3 pm during January in Townsville.

Directions	Windspeed intervals (metres per second)						
	Calms	0.5-1.5	2.0-3.0	3.6-5.0	5.7-8.2	8.7-10.8	Total(%)
	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 4: Percentage Distribution of 10 m Winds at 3 pm at Townsville during January.

From Table 4 percentage occurrences of northerly winds for all windspeed intervals exceeding 1.15 m/s are 3.9% for 2.0 to 3.0 m/s; 8.4% for 3.6 to 5.0 m/s; 2.6% for 5.7 to 8.2 m/s and 0.6% for 8.7 to 10.8 m/s, giving a total of 15.5% of time when northerly winds will restore comfort. This process is repeated (Table 5) for each wind direction until one obtains a total percentage of time during which comfort is likely to be maintained.

Direction	$C_{\bar{V}_1}$	10m $\bar{V}$ to restore comfort (0.83/$C_{\bar{V}}$) m/s	Cumulative Percentage of time winds exceed %
N	0.72	1.15	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%

Table 5: Total Percentage of Time during which Comfort is likely to be maintained for all Wind Directions.

The actual percentage of time that thermal comfort can be maintained will be higher than the estimated 87.0 percent because all windspeeds through the living area (with a 2 m/s external reference windspeed) exceed by a significant amount the minimum internal windspeed for thermal comfort of 0.83 m/s. However the size of windspeed increments provided in the available wind data 0.5-1.5 and 2.0-3.0 m/s prevent a more accurate appraisal.

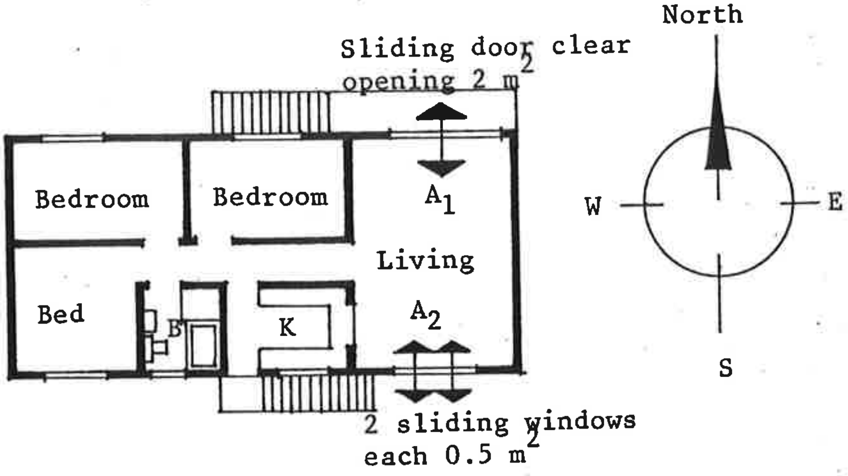
The remaining periods of time when thermal comfort cannot be achieved by natural ventilation, that is less than 13 percent, should be catered for by the occasional use of ceiling fans.

APPENDIX 2.

Example

Determination of the extent to which natural ventilation is likely to maintain comfort in the living room of the isolated high set house (Fig.7) in Townsville at 3 pm during January using the discharge equation.

Figure 7:
Plan of High Set House Showing Living room Wall Openings.



Climatic Data

3 pm, 86 percentile average maximum dry bulb temperature for January = 32.9°C

3 pm 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 5 is 0.83 m/s.

Windspeed frequency and directions for Townsville at 3 pm during January are indicated in Table 4. It would be reasonable to expect this data to be respresentative of most Townsville suburbs as there is no significant change in terrain over most of the suburban area.

Building Data

Orientation and layout of isolated high set house are as indicated in Figure 7.

Openings in living room walls:

	Dimensions	Clear area of Opening
Sliding door north facing wall	2 m x 1 m	2.0 m^2
2 sliding windows south facing wall	1 m x 0.5m 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°

Pressure coefficients at locations near openings from Aynsley (Ref.5):

Windward	+0.33
Leeward	-0.38

Free area of windward opening = 2 m^2

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

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

Discharge coefficient from Figure 7 for windward opening with two edges common with downwind space = 0.75

Free area of leeward openings = 1 m^2

Discharge coefficient for leeward openings from Figure 8 with an A_o/A_1 ratio of 1/12th or 0.08 = 0.63

Discharge Q, to achieve thermal comfort at the windward opening is the product of the effective area of the opening ($A_1 \text{Cos } \theta$) and the minimum windspeed for thermal comfort 0.83 m/s, that is:

$$\begin{aligned} Q &= A_1 \text{Cos } \theta\ \bar{V}_1 \\ &= 2 \times 0.707 \times 0.83 \\ &= 1.17\ m^3/s \end{aligned}$$

Equation 6 can be rearranged to solve for the windspeed 10 m above ground needed to achieve the above discharge rate and corresponding minimum indoor windspeed for thermal comfort.

$$V_{10} = \frac{A_1 \text{Cos } \theta\ \bar{V}_1}{\left[\dfrac{(C_{P1} - C_{P2})}{\dfrac{1}{{Cd_1}^2{A_1}^2} + \dfrac{1}{{Cd_2}^2{A_2}^2}}\right]^{\frac{1}{2}}}$$

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

$$= 2.63\ m/s$$

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

$$A = A_2V_2$$
$$= 1 \times 0.83$$
$$= 0.83\ m^3/s$$

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

$$V_{10} = \frac{0.8}{\left(\dfrac{(0.30 - (-0.38))}{\dfrac{1}{0.75^2 \times 1.4^2} + \dfrac{1}{0.63^2 \times 1^2}}\right)^{\frac{1}{2}}}$$

$$= 1.87\ m/s$$

Clearly for winds from the North East the governing 10 m windspeed requirement is 2.63 m/s for the windward opening, which falls within the 2.0 - 3.0 m/s 10m windspeed interval on the wind frequency table (Figure 4).

Summing the percentage occurrence of higher windspeed intervals 3.6 - 5.0 m/s of 14.3% and 5.7 - 8.2 m/s of 12.3% for the North East direction gives a total of 26.6% of time.

Wind direction	Incidence θ	C_{p1}	C_{p2}	A_1	A_1Cos θ	A_2	A_2Cos θ	C_{d1}	C_{d2}	Minimum windspeed interval for thermal comfort	% Occurrence of thermal comfort
NNE	22½	0.36	0	2	1.8	1	-	0.75	0.63	5.7	3.2
NE	45	0.30	-0.38	2	1.4	1	-	0.75	0.63	3.6	26.6
ENE	67½	0.14	-0.07	2	0.77	1	-	0.75	0.63	5.7	7.8
ESE	67½	-0.07	0.14	2	-	1	0.38	0.64	0.70	14.4	-
SE	45	-0.38	0.30	2	-	1	0.71	0.64	0.70	5.7	-
SW	45	-0.16	0	2	-	1	0.71	0.64	0.70	11.3	-
NW	45	0.0	-0.16	2	1.4	1	-	0.75	0.63	5.7	-
NNW	22½	0.16	-0.07	2	1.8	1	-	0.75	0.63	5.7	0.6
N	0	0.55	-0.12	2	2.0	1	-	0.75	0.63	3.6	11.6
										TOTAL	49.8 %

Table 6: Total Percentage of Time during which Comfort is Likely to be Maintained for all Wind Directions.

When all wind directions are considered (Table 6) 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 pm during the month of January.