EFFECTIVE VENTILATION

9th AIVC Conference, Gent, Belgium
12-15 September, 1988

Paper 20

NATURAL VENTILATION FOR A CROWN COURT: DEVELOPING STATISTICAL ASSESSMENT TECHNIQUES AT THE DESIGN STAGE

M.D.A.E.S. PERERA, R.R. WALKER AND R.G. TULL

Building Research Establishment
UK Department of the Environment
Garston
Watford
U.K.

SYNOPSIS

The ventilation performance of a proposed naturally-ventilated court-room was predicted and assessed on a statistical basis with regard to the local meteorological conditions. Summertime ventilation was to be provided via an underfloor duct and controllable vents at roof levels, under the action of wind and buoyancy forces.

Wind pressure coefficients expected on the external facade of the building were obtained from wind tunnel measurements on a scale model. Treating the court-room as a single cell, a computer prediction program was used to determine ventilation flows into the building for various configurations of ventilation openings, and a range of meteorological conditions and internal temperatures. For each wind direction, ventilation flows versus windspeed were presented in a convenient compressed form, in which the temperature dependence was removed.

A new approach was developed to predict the statistical occurrence of design ventilation levels by using the above results with correlated frequency distributions of the local meteorological data.

1. INTRODUCTION

A Law Courts Complex, comprising of several Crown Courts and one County Court, is to be built at a site in Canterbury, and a requirement for this project is that, if possible, court-rooms are naturally ventilated and air conditioning is avoided.

The system for naturally ventilating the court-rooms depends primarily on introducing fresh air through underfloor ducts and venting contaminated air out through high level vents, under the action of stack and wind pressures. Design objectives require this system to provide the necessary fresh air for summertime conditions. Fresh air ventilation requirements are set at 1000 m^3/hr and 2000 m^3/hr for conditions representing average and full court-room occupancy patterns respectively.

The complexity of the building layout makes it very difficult, if not impossible, to use existing design guides[1,2] to predict whether the court-rooms will be adequately ventilated. Computer models are therefore required. Computer prediction requires two major items of input data - leakage characteristics of the building fabric and the distribution of wind pressures on its external facade. If computer prediction is carried out with the intentional openings (vents, windows and ducts) opened, then it is possible to restrict input data to those components and neglect 'background' leakage through cracks etc.

Tabulated values of surface pressures are available for simple building forms[1,3]. For more complex buildings, however, an individual wind tunnel test is needed. Within such a test, the buildings and the surroundings need to be modelled as faithfully as possible and then tested in a simulated airflow which represents that flowing over the corresponding full-scale terrain.

This paper begins by describing a wind tunnel test to measure surface wind pressures on a model of the proposed court complex. A single-cell computer prediction program then uses these measurements to determine ventilation flows into a typical court-room for various configurations of ventilation openings over a wide range of meteorological conditions and internal temperatures. It is shown that for each wind direction, ventilation flows versus windspeed can be presented in a convenient compressed form (an example is given), in which the temperature dependence is removed.

The paper concludes by describing a new approach developed to predict the statistical occurrence of design ventilation levels by considering the frequency distribution of the local meteorological data.

2. WIND TUNNEL TESTS

It is generally accepted that if the air flow in the wind tunnel conforms to certain conditions, then

- the pattern of flow,
- the distribution of wind speeds around a properly scaled model, and
- the distribution of wind pressures on the external surface of the model

will be similar to that around a full-scale development.

The conditions required for this to be met are that:

- there should be an increase in velocity with height in the airstream similar to that of the atmospheric boundary layer (ABL) flowing over a terrain similar to that of the site under consideration, and
- there should be a distribution of scales of turbulence in the wind tunnel airstream similar to that on full scale with the size of the turbulent eddies reduced to match the model size.

Figure 1 shows a schematic view of the 2.00 m x 1.25 m BRE Environmental Wind Tunnel (EWT). In the EWT, a 1:250 length scale suburban boundary layer was simulated using a bi-planar grid and a saw-tooth fence to start the required layer and then letting it develop over eight metres of roughened surface. The simulated boundary layer then flows over and around the model which is placed on the turntable in the working area.

Constraints, such as the amount of detail that needed to be modelled, required the model to be a 1:150th representation of full-scale. The existing boundary-layer simulation was considered to be adequate, on the grounds that averaged pressures (in which we are interested) do not vary substantially with changes in length scales.

The model of the court complex (containing 47 surface pressure tappings) together with outlying buildings in its near vicinity was mounted on a 1.75 m diameter turntable. This was placed in the wind tunnel and rotated under computer control to simulate different wind directions.

All pressures measured were referenced to the dynamic pressure, P_D, of the airstream measured at a location well upstream of the model under test. The height of the reference location was chosen by considering the anemometer height of the nearest meteorological station. This was set at a height of 12 cm (18 m full scale) representing the anemometer mast height at the meteorological station at Manston, 20 km ENE of Canterbury.

The pressure P_D in Pascals (Pa) is related to the wind tunnel reference velocity, U_{ref} in m/s, by the relationship

$$P_D = \frac{1}{2}\rho U^2_{ref}$$

where the density of air, $\rho = 1.225$ kg/m^3.

Pressures, P, measured at various surface pressure ports are then normalised by P_D to give the surface pressure coefficients, C_p, such that

$$C_p = P / P_D$$

A valid assumption for this model, with well-defined edges where wind separates, is that the pressure coefficients so evaluated are independent of windspeeds used in subsequent calculations. This independence allows us to calculate any other pressure P corresponding to a velocity U by using the equation,

$$P = \tfrac{1}{2}\rho U^2 C_p$$

For this series of tests, the reference wind speed was set to about 6.5 m/s. The modelling procedure allows us to choose the velocity scaling as 1:1 so that windspeeds in the wind tunnel are equivalent to those at full scale. With the length scale of 1:150, the time scale is also 1:150.

Each pressure port was connected (under computer control) to a pressure transducer and the resulting analogue signal was digitised at a rate of 512 samples/sec for a 60-sec period. Each of the pressure ports therefore yielded for processing about 30,000 raw data values for every incident wind direction tested. On-line analysis computed each 60-second mean value together with other statistical information. It should be noted that the 1-minute mean values correspond to 150-minute averages in full scale.

After each test run, the turntable was rotated to a new wind direction and the above tests repeated. In all, tests were carried out at the 12 principal wind directions from 0^{o} to 330^{o}N in steps of 30^{o}.

3. VENTILATION PREDICTION

A computer program was written which comprised of equations (Appendix) relating the airflow through each type of ventilation opening to the pressure difference across each opening. These pressure differences depend on the wind speed and direction and on the pressure coefficients exterior to the opening, and also on the temperature difference between the air in the room and that outside. The room air pressure is the unknown parameter to be found. The computer program uses an iterative procedure to repeatedly calculate the airflows through each of the openings until mass balance is satisfied for a unique choice of internal air pressure.

Figure 2 shows a sectional schematic drawing of one of the court-rooms used to derive the model. It consists of an underfloor duct, two mid-level windows on opposite faces and four high-level vents on each face of a podium-like structure. Though many open/closed combinations were tested, the configuration discussed in this paper relates to the case where both the windows and the windward vent are closed. The 'windward vent' is interpreted as the one for which the normal to its outward face is within 45^{o} of the direction from which the wind is blowing.

It is necessary to compute the ventilation flow for wind blowing from each direction for a range of windspeeds and differences in air temperature between inside and outside of the court. To avoid generating a large and unmanageable set of data, the results need to be presented in a compressed form, in which the temperature dependance has been removed, without any loss in generality.

For each wind direction, all this information can be collapsed[4,5], and the temperature dependence removed, by scaling both the ventilation flow Q_v and the windspeed U by the factor $1/\sqrt{(T_i - T_o)}$, where T_i and T_o are the internal and outside air temperatures respectively. This approach was validated, over the current range of interest, for both Q_v

and the flow Q_d through the duct. Results for the latter are shown in Figure 3a and it also should be noted that Q_d is the likeliest source of ventilation to the occupied region.

Figure 3b shows a selection of results for Q_d, for 90^0 intervals, to include the only example for which there is a risk of stagnation of flow in the duct. Generally ventilation supplied via the duct is in excess of 2300 m^3/hr for all temperatures. The exception occurs for wind from direction 210^0 (SSW).

A 1^oC temperature difference enables the requirement for part occupancy to be met for windspeeds less than approximately 5.2 m/s, and up to approximately 3.4 m/s for full occupancy. When the temperature difference is between 3 - 4^oC, both requirements are met for windspeeds up to around 10 m/s.

4. STATISTICAL ASSESSMENT

The ventilation prediction carried out above, though specific to the court-room, makes no reference, however, to the local climatic conditions expected at the site. To assess whether or not adequate ventilation would be available in these court-rooms, further refinement of the results is necessary.

This was accomplished by combining the expected climatic conditions at the Chaucer site with the ventilation characteristics of the proposed ventilation configuration for the court-rooms, to give a statistical measure of how often various levels of ventilation could be expected. The results were further refined by constraining the analysis to the occupied hours between 0900 to 1800 hrs during the Spring/Summer months.

A measure of the climatic conditions at the site was obtained from the nearest meteorological station - Manston. Manston station lies on an airfield characteristic of open countryside terrain while the Canterbury site is more representative of a rural terrain with scattered windbreaks. This change of terrain means that wind speeds at the site would be reduced in comparison to that measured at Manston. Calculations[3] indicate that windspeeds at the site would be 83% of that experienced at Manston.

For the period considered, Figure 4.a shows the percentage frequency of occurrence of wind direction at Canterbury. Though there is no dominant direction, there is a higher occurrence of winds from both NNE and from the SW. Average windspeed for the site is estimated as 5.6 m/s from Figure 4.b Similarly, the average outside air temperature is estimated as 17^oC from Figure 4.c.

The ventilation performance of the court-rooms is determined both by wind pressure and buoyancy forces. Therefore, it is necessary to know the joint occurrence of both windspeed and outside air temperature. Consequently, the percentage occurrences of windspeed versus outside air temperature for each of the 30^0 sector wind directions was obtained for Manston, as shown in Table 1, for the example of northerly winds. Subsequently, windspeeds were corrected for Canterbury as discussed earlier.

Provided the internal temperature, T_i, of the court-room is decided, or can be maintained, it is a simple matter to determine the duct flow, Q_d, for a given choice of windspeed U and outside air temperature, T_o corresponding to the values given in the joint occurrence table (e.g. Table 1). The duct flow is computed from empirical fifth-order polynomials, shown below, which are curve-fits to the duct flow results:

$$\acute{Q}_d = a_o + a_1\acute{U} + a_2\acute{U}^2 + a_3\acute{U}^3 + a_4\acute{U}^4 + a_5\acute{U}^5$$

where,

$$\acute{Q}_d = Q_d/\surd(T_i - T_o)$$

$$\acute{U} = U/\surd(T_i - T_o)$$

$$a_o, a_1, \ldots = \text{constants}$$

The percentage occurence of each duct flow is then read from the Table and placed in *bins* corresponding to various intervals of duct flows. This allows a probability distribution to be gradually built up for each wind direction.

The procedure is repeated for each of the twelve wind directions until the final distribution is complete. This is then easily transformed into a cumulative distribution plot so that percentage exceedance of duct flows can be determined. A computer *spreadsheet* program was used to evaluate this distribution, and proved instructive for handling the large quantities of tabulated data involved.

Expected fresh air ventilation into the court-room was assessed for the occupied periods (0900 to 1800 hrs) during the Spring/Summer months. A constant internal temperature has been assumed ; it is recognised that this is unrealistic where there is a close mutual interaction between ventilation and internal temperature. However, for a full analysis it is necessary to use a complex simulation model to calculate the internal temperature corresponding to all occurences of external temperature, wind speed and wind direction, and then compute the ventilation rate for each combination, in an iterative manner. The feasibility of using such a simulation model in this way is being explored, but the difficulties should not be underestimated.

For the present purposes two internal temperatures were considered[6]; a maximum design level of 25°C and the expected average (50% of the time) level of 21°C. Figures 5.a and 5.b show the expected percentage probability of exceedance of the duct flows for each of the two internal temperatures respectively. These results may be compared with the ventilation requirements stated above (Section 1).

5. CONCLUSIONS

Passive ventilation of one of the court-rooms to be built at Canterbury was assessed taking into consideration the meteorological conditions expected during the spring/summer months. The methodology introduced for dealing with meteorological data on a statistical basis represents a significant step forward. The analysis was constrained by considering the period (0900 to 1800 hrs) during which the court was expected to be occupied. Constant internal temperatures were assumed, with no mutual interaction with ventilation. This simplification of the actual ventilation mechanisms that will apply in the building when constructed will be examined in further studies.

With the windward upper-vent closed, the other three vents open and all mid-level windows closed, the expected percentage probability of exceedance of the duct flow was computed for each of the two internal temperatures respectively. With an internal temperature of 21°C, results indicate that ventilation requirement for either full or part occupancy is met for about 90% of the time. If the internal temperature rises to 25°C, the increase in the buoyancy effect increases the period of adequate ventilation to include nearly all the time that the court is occupied.

ACKNOWLEDGEMENTS

Thanks are due to Dr P R Warren for suggesting the approach to data-compression regarding temperature, and to J O'Dowd for initial help with the computing. The work described here has been carried out by the Building Research Establishment of the Department of the Environment as part of the research programme for the Property Services Agency (PSA).

REFERENCES

1. British Standards Institute, Code of Practice for Design of Buildings: Ventilation Principles and Designing for Natural Ventilation, BS 5925, (1980).

2. CIBS, Guide A4: Air Infiltration, The Chartered Institute of Building Services, London (1976).

3. Liddament, M W, Air Infiltration Calculation Techniques - An Applications Guide, Air Infiltration Centre, Bracknell (1986).

4. Warren, P R and Webb, B C, The relationship between tracer gas and pressurisation techniques in dwellings, Proceedings of the 1st AIC Conference on Infiltration Measurement Techniques, held in London (1980).

5. Warren, P R and Webb, B C, Ventilation measurements in housing, Proceedings of the CIBS Symposium on Natural Ventilation by Design, held at BRE, Garston (December 1980).

6. Pinney, A, Private communication, unpublished internal BRE report (1987).

APPENDIX

COMPUTER MODEL ALGORITHMS

The following expressions were used to calculate the airflow through each ventilation opening (element). These formed the basis of the computer program used.

The density of air flowing through any element is that of air either at the external or the internal temperature, depending on whether flow is directed either into or out from the building. This is signified by the sign of the pressure drop across the element, which is correspondingly either positive or negative. Volume flow balance is employed as the basis for the iteration procedure to obtain solutions for the flow through each element; for this purpose volume flow rates are computed as the equivalent flow rate of air at the external temperature.

Flow through ductwork

$\Delta P > 0$ (flow into building): $\Delta P < 0$ (outflow from building):

$$Q_d = k\ [\ \Delta P\ /\ \rho_o\ ]^{1/2} \qquad Q_d = -\ k\ [\ |\Delta P|\ /\ \rho_i\ ]^{1/2}\ \rho_i/\rho_o$$

where in both cases $\Delta P = \tfrac{1}{2}\rho_o U^2\ (\ C_{pj} - C_{pi}\ )$. There is no buoyancy term as the duct is horizontal.

k is manually estimated beforehand using $Q_r = k\ (\ \Delta P_r\ /\ \rho_r\ )^{1/2}$, where ΔP_r is the sum of the pressure losses estimated across the various component parts of the ductwork for reference values of density, ρ_r, and flow rate, Q_r. Defined in this way, k is independent of the flow density. It should be noted that in this case Q_r was necessarily small, causing estimates of pressure loss to be very approximate.

Flow through windows and vents

$\Delta P > 0$ (flow into building): $\Delta P < 0$ (outflow from building):

$$Q_j = A\ C_d\ [\ \Delta P\ /\ \tfrac{1}{2}\rho_o\ ]^{1/2} \qquad Q_j = -\ A\ C_d\ [\ |\Delta P|\ /\ \tfrac{1}{2}\rho_i\ ]^{1/2}\ \rho_i/\rho_o$$

where in both cases $\Delta P = \tfrac{1}{2}\rho_o U^2\ (\ C_{pj} - C_{pi}\ ) - (\ \rho_o - \rho_i\ )\ g\ h$.

The 'internal pressure coefficient', C_{pi}, has been introduced for convenience, and is defined as follows:

$$C_{pi} = (\ P_i - P_o\ )\ /\ \tfrac{1}{2}\rho_o\ U^2$$

where:

P_i = static internal pressure
P_o = static external pressure.

Notation

A_j	Open area of ventilation element (vent or window)
C_d	Discharge coefficient of ventilation element (vent or window)
C_{pi}	Internal pressure coefficient (see above)
C_{pj}	Pressure coefficient at location of ventilation element
g	Acceleration do to gravity
h	Height of lower extremity of ventilation element
K	Duct flow pressure-loss lumped parameter
ΔP	Total pressure loss across a ventilation element
Q_d	Volume flow rate through duct
Q_j	Volume flow rate through vent or window
Q_v	Total volume flow rate into building
Q	Net volume flow rate into building
ρ_i, ρ_o	Internal and external air densities

```
MANSTON
                       PERIOD:   1/ 1/1971 TO 31/12/1980             PAGE   1
                       MONTHS AND HOURS USED:    SEE HEADING PAGE
MEAN HOURLY WIND DIRECTION(TRUE)   346 TO    15

FREQUENCY TABLE
                                MEAN HOURLY WIND SPEED (KNOTS)

LOWER BOUNDARY          0     0     1     3     6     9    12    15    18    21    24    27
UPPER BOUNDARY         -1     0     2     5     8    11    14    17    20    23    26   999 TOTAL

DRY BULB TEMPERATURE (0.1C)
  < OR =     50         0     0     0     0     4     3     4     5     2     2     0     0    20
   51 TO     70         4     1     1     7    18    20    20    21     9     8     1     0   110
   71 TO     90         4     4     2    13    30    27    48    28    15    10     5     0   186
   91 TO    110         6     6     4    21    36    35    29    31    18     3     4     2   195
  111 TO    130         3     2     4    13    32    45    51    44    20     7     2     4   227
  131 TO    150         9     0     5    21    48    32    63    46    32    11     1     0   268
  151 TO    170        21     3     5    26    60    64    61    49    19     1     2     0   311
  171 TO    190        18     5     2    34    89    35    27    17     8     4     4     0   243
  191 TO    210        15     1     3     9    37    14     5     1     1     0     0     0    86
  211 TO    250         9     0     1    13    30     6     1     0     0     0     0     0    60
  251 TO    270         3     0     0     3     1     0     0     0     0     0     0     0     7
  271 TO    999         1     0     0     1     2     0     0     0     0     0     0     0     4

      TOTALS           93    22    27   161   387   281   309   242   124    46    19     6  1717


PERCENTAGE FREQUENCY TABLE
                                MEAN HOURLY WIND SPEED (KNOTS)

LOWER BOUNDARY          0     0     1     3     6     9    12    15    18    21    24    27
UPPER BOUNDARY         -1     0     2     5     8    11    14    17    20    23    26   999 TOTAL

DRY BULB TEMPERATURE (0.1C)
  < OR =     50       0.0   0.0   0.0   0.0   0.2   0.2   0.2   0.3   0.1   0.1   0.0   0.0   1.2
   51 TO     70       0.2   0.1   0.1   0.4   1.0   1.2   1.2   1.2   0.5   0.5   0.1   0.0   6.4
   71 TO     90       0.2   0.2   0.1   0.8   1.7   1.6   2.8   1.6   0.9   0.6   0.3   0.0  10.8
   91 TO    110       0.3   0.3   0.2   1.2   2.1   2.0   1.7   1.8   1.0   0.2   0.2   0.1  11.4
  111 TO    130       0.2   0.1   0.2   0.8   1.9   2.6   3.0   2.6   1.2   0.4   0.1   0.2  13.2
  131 TO    150       0.5   0.0   0.3   1.2   2.8   1.9   3.7   2.7   1.9   0.6   0.1   0.0  15.6
  151 TO    170       1.2   0.2   0.3   1.5   3.5   3.7   3.6   2.9   1.1   0.1   0.1   0.0  18.1
  171 TO    190       1.0   0.3   0.1   2.0   5.2   2.0   1.6   1.0   0.5   0.2   0.2   0.0  14.2
  191 TO    210       0.9   0.1   0.2   0.5   2.2   0.8   0.3   0.1   0.1   0.0   0.0   0.0   5.0
  211 TO    250       0.5   0.0   0.1   0.8   1.7   0.3   0.1   0.0   0.0   0.0   0.0   0.0   3.5
  251 TO    270       0.2   0.0   0.0   0.2   0.1   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.4
  271 TO    999       0.1   0.0   0.0   0.1   0.1   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.2

      TOTALS          5.4   1.3   1.6   9.4  22.5  16.4  .8.0  14.1   7.2   2.7   1.1   0.3 100.0
```

TABLE 1 Frequency of occurence of air temperature with wind speeds at Canterbury

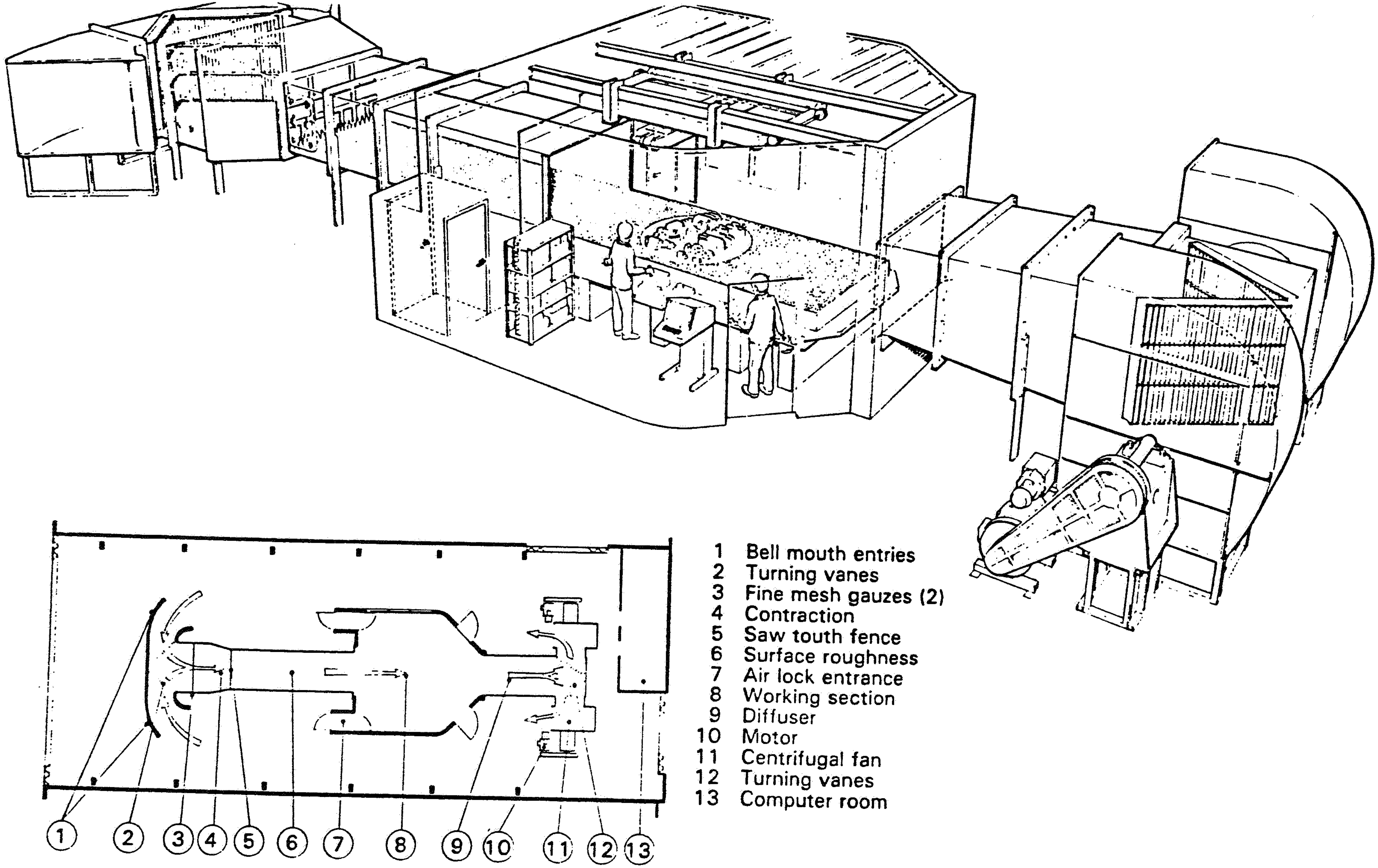

Figure 1 BRE Environmental wind tunnel

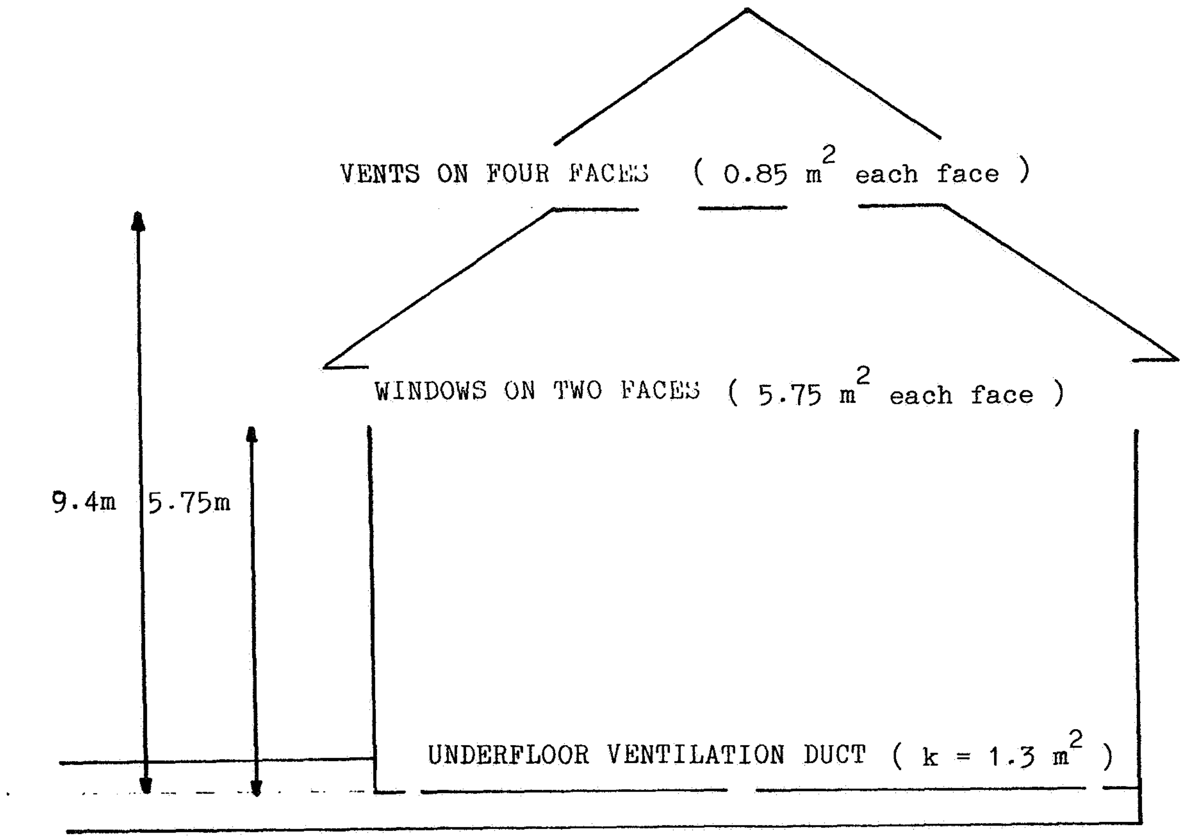

FIG. 2 Schematic representation of court-room

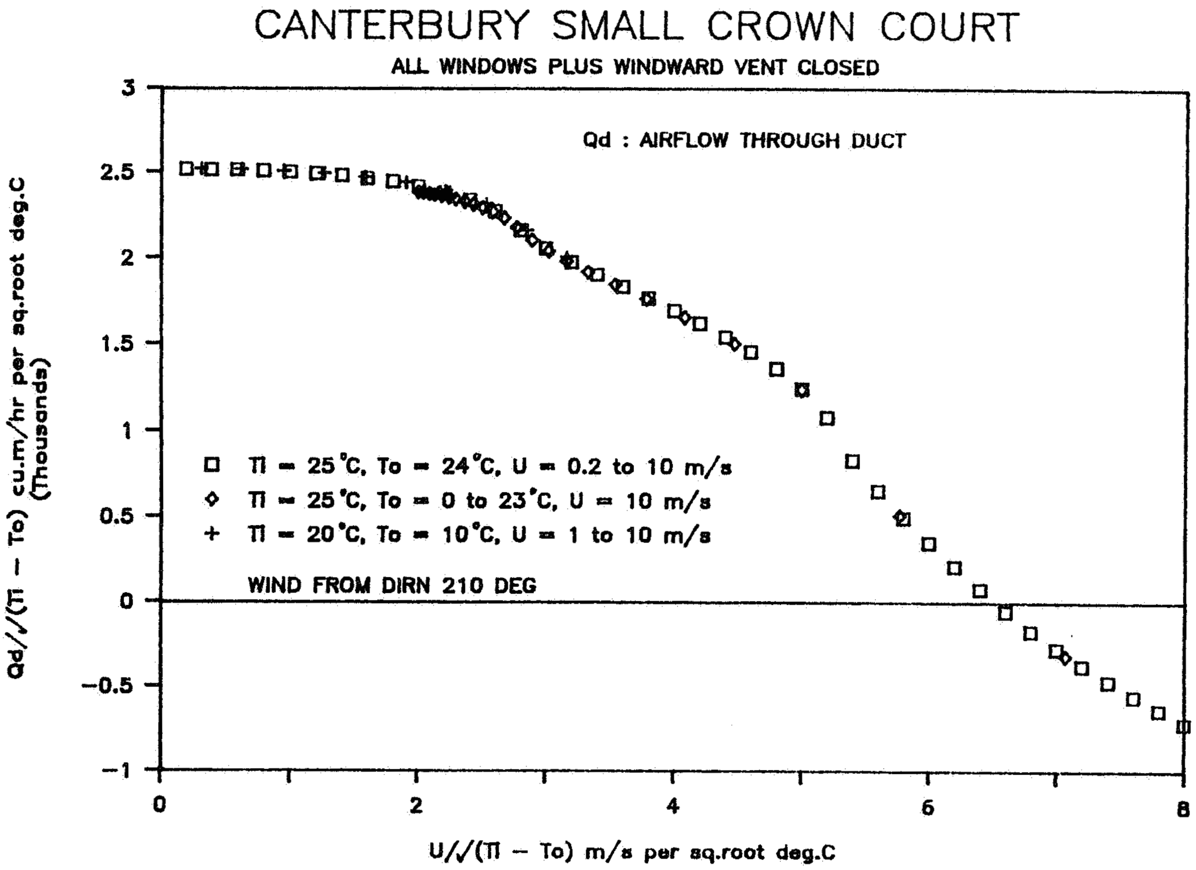

FIG. 3.a Collapsed curves: dependence on temperature-difference removed

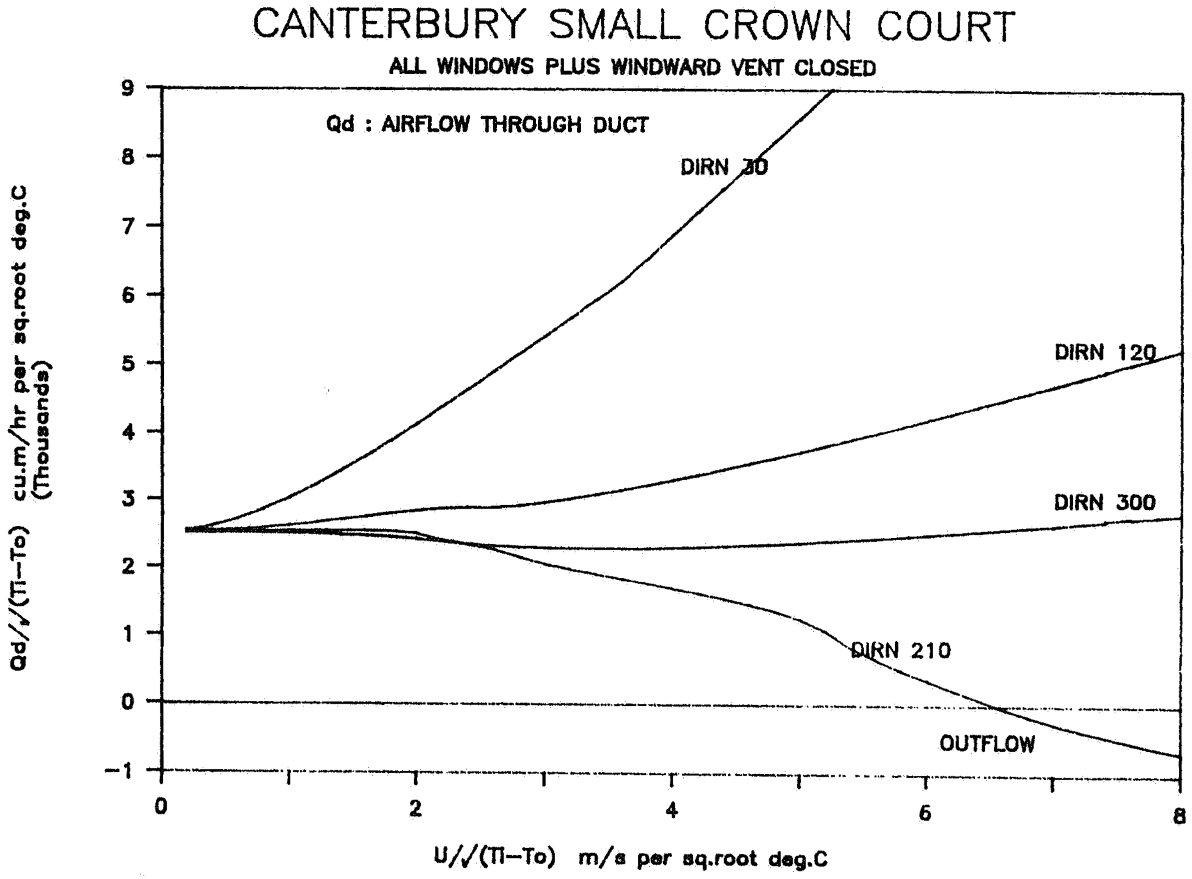

FIG. 3.b Selection of results for 90° intervals

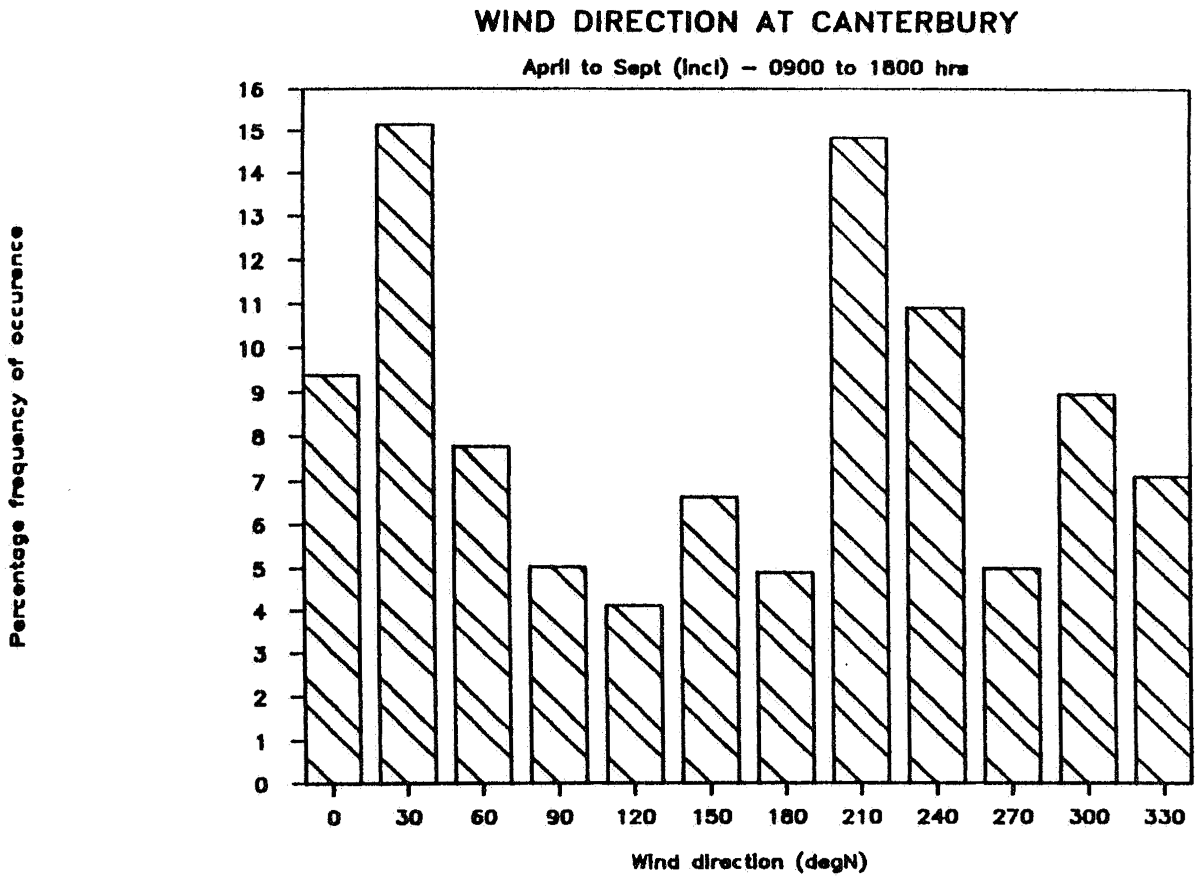

FIG. 4.a Frequency of occurrence - wind direction at Canterbury

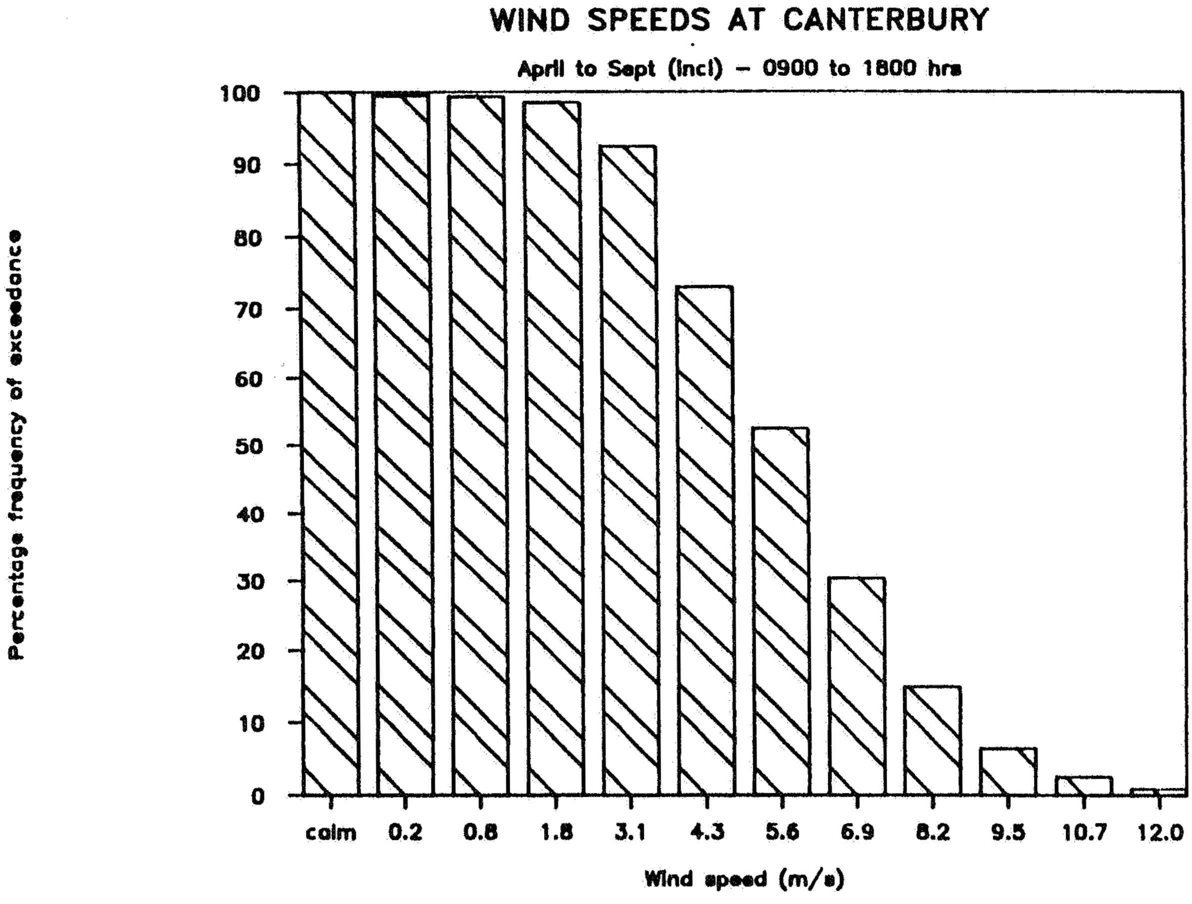

FIG. 4.b Frequency of exceedence - wind speeds at Canterbury

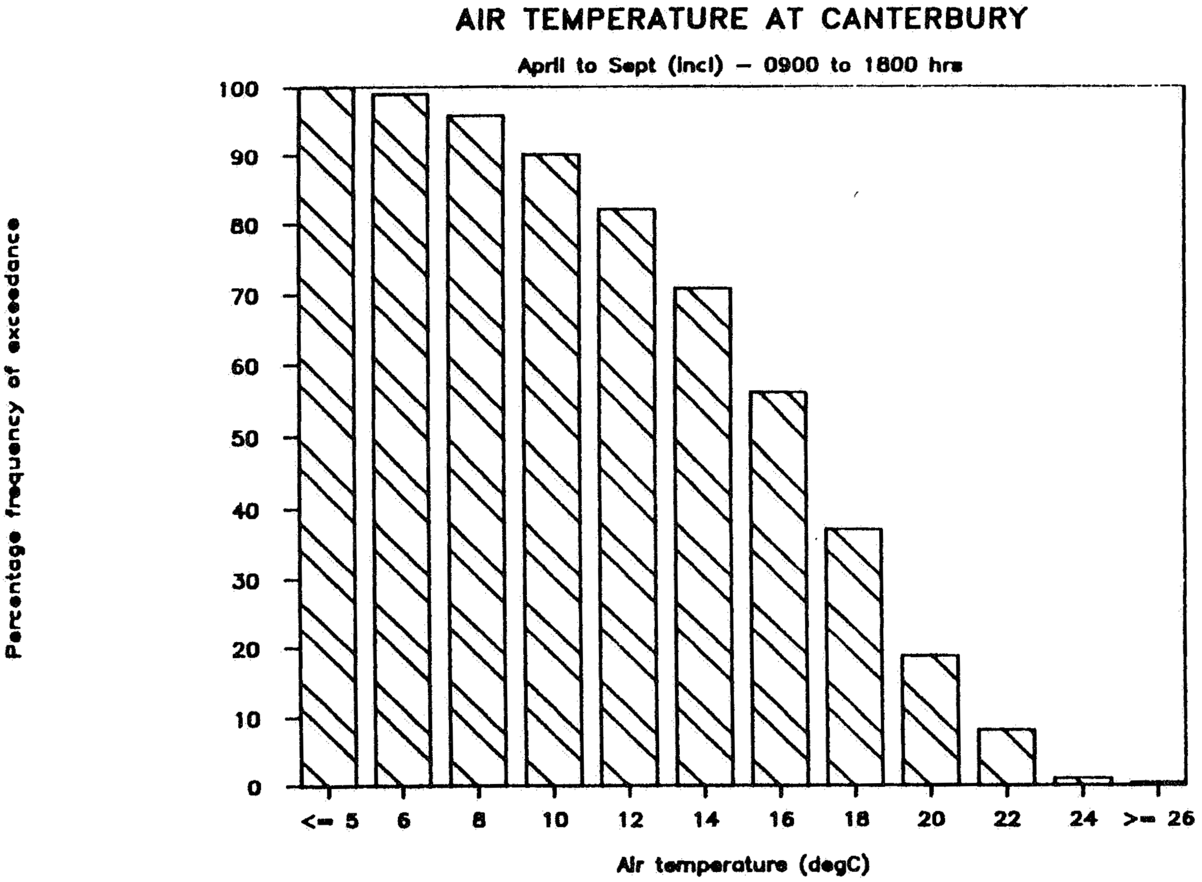

FIG. 4.c Frequency of exceedence - air temperature at Canterbury

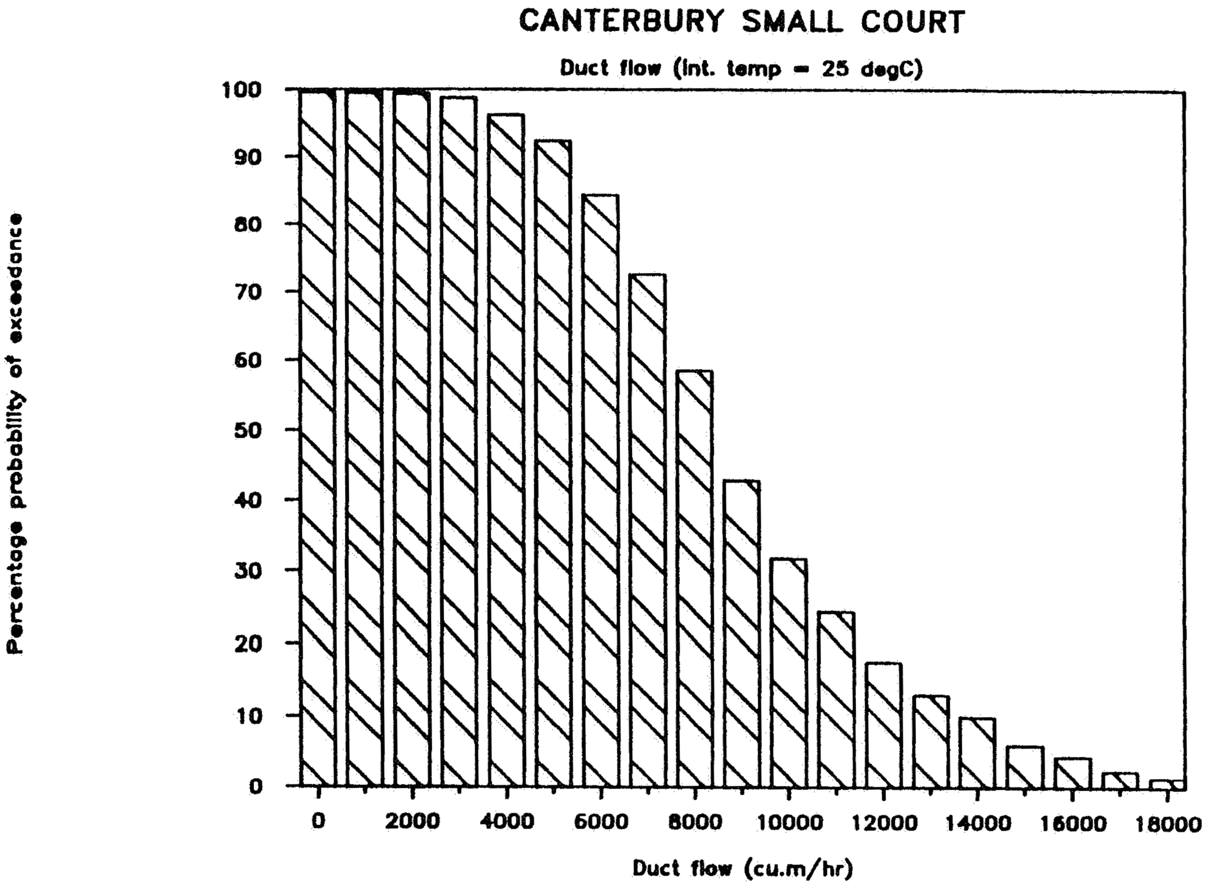

FIG. 5.a Probability of exceedence - duct flow for court at 25°C

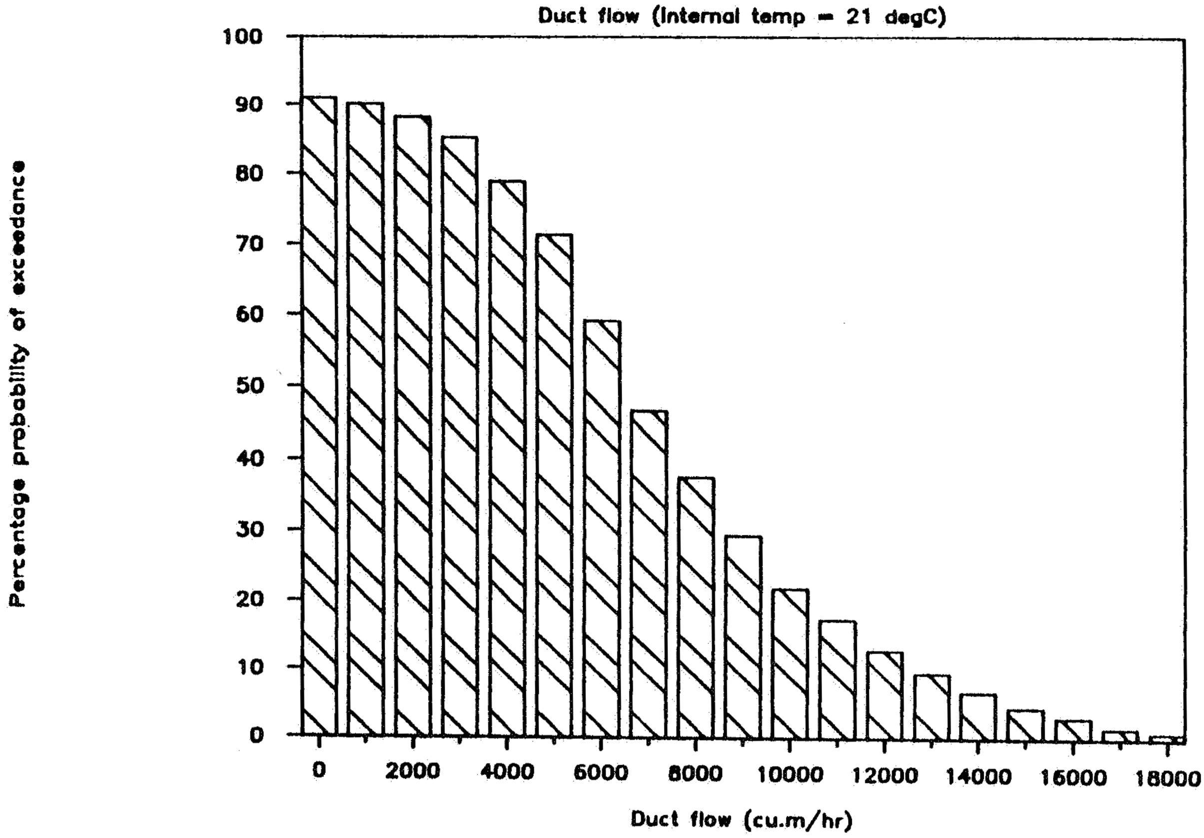

FIG. 5.b Probability of exceedence - duct flow for court at 21°C

Discussion

Paper 20

C-A. Roulet (Ecole Polytechnique Federale de Lausanne, Switzerland)
Do you plan to verify your computations with tracer gas measurements?

R. Walker (Building Research Station, Garston, UK) Yes, we plan to follow up our predictions with measurements - the court has not yet been built.