Summary In countries such as the United Kingdom that possess a temperate climate, the majority of buildings are not air-conditioned but depend upon natural ventilation and relatively simple heating systems. Openable windows are used to reduce the incidence of summertime overheating. Studies on housing have indicated, however, that window opening also occurs extensively through the heating season, resulting in substantial heat loss and consequent energy consumption. This paper describes the results of an initial investigation to determine whether the same phenomenon occurs in office buildings. Observations were made of the use of windows in five office buildings over a three-month period, covering a range of weather conditions. The proportion of windows open was found to be closely correlated with external air temperature and to be affected, also, by solar gain and wind speed. A more detailed analysis suggested two modes of window use, one related to the need to maintain adequate indoor air quality and the second to the need to control indoor air temperature. The results, although only for a limited range of office buildings, indicated that the heat loss resulting from the use of windows, rather than other forms of heating control, could make a significant contribution to thermal performance and energy consumption. It is concluded that further work is required to develop methods for taking window use into account in building design and performance calculations.

Window-opening behaviour in office buildings

P. R. WARREN, BA, PhD, and L. M. PARKINS

1 Introduction

In a temperate climate such as that of the United Kingdom, air conditioning, while advisable for full control of the indoor climate, is not a necessity for the majority of buildings. In summer the incidence of excessive internal temperatures can be limited by a combination of appropriate thermal design, solar protection and natural ventilation. Natural ventilation is generally provided by the use of openable windows, which, together with other adaptive mechanisms[1], such as changes in activity, posture, and clothing, allows occupants to optimise their level of thermal comfort within the constraints provided by the building and social acceptability. Window opening may modify the internal environment in two ways, first, by increasing natural ventilation and, second, by increasing air velocities.

During the heating season, adequate control of the input to a space from the heating system should ensure comfortable conditions. This may be achieved automatically, but generally some degree of manual control, for instance, by the use of a radiator valve, is available to the occupant. Window opening should, in principle, only be necessary where natural ventilation, additional to that occurring adventitiously by infiltration, is needed to assist in the control of indoor air quality by diluting internally generated pollutants.

Any level of ventilation over and above this will result in unnecessary heat loss. This possibility is not generally taken into account in methods of calculating the thermal performance of buildings and energy consumption. There have been a number of studies[2,3,4,5,6] seeking to understand better the factors that affect window opening in houses.

This paper describes the results of a preliminary study to determine to what degree window opening occurs in naturally ventilated office buildings and what factors influence this behaviour.

2 Previous studies of window opening

Dick[2] observed window opening in two sets of houses as part of a major investigation of domestic heating during the immediate post-war period in the United Kingdom. In the larger set, consisting of 15 houses on a relatively exposed site, he was able to demonstrate that the average number of windows open per house was positively correlated with external air temperature and that this alone accounted for 70 per cent of the observed variance in window opening. An additional 10 per cent of the variance was attributable to wind speed, which had a negative effect. Dick used these results, in conjunction with tracer gas measurements of ventilation rate, to estimate the weekly mean ventilation rates in the occupied houses and, hence, to determine the additional energy consumption over and above that due to infiltration alone. On the average, taken over the whole heating season, an additional one air change per hour was attributable to the use of windows.

More recently Brundrett[3,4,5] has carried out a number of investigations designed to gain further insight into window-opening behaviour and to understand the motivation of occupants. These studies were limited to housing but consisted both of observations of window use and of questionnaire surveys of occupants. He confirmed Dick's findings that the average number of open windows per house was strongly correlated with external air temperature and modified by wind speed. Window opening was also seen to be related to other factors, such as family size and patterns of occupancy. In examining the motives for window opening, he noted that in the relatively damp climate of the United Kingdom the dry-bulb temperature and moisture content of the outdoor air are closely correlated for much of the heating season. He suggested that a possible motive for the observed increase in window opening with temperature is the need for increased ventilation to control indoor humidity.

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Lyberg[6], quoting work by Holm *et al*[7] in addition to his own, has shown that window opening also occurs during the heating season in Swedish residential buildings. Lyberg analysed his observations in terms of the difference in temperature between indoor and outdoor air but showed that the results were consistent with those of Dick[2] and Brundrett[4].

Few observations have been made in buildings other than dwellings. Humphreys and Nicol[1] noted a strong correlation ($r = 0.71$; $df = 71$) between the number of windows open in a school building in summer and the outdoor temperature. Pallot[8] reported an investigation of window opening in a large London office building, made during the 1951-52 heating season. The building had a total of 1,164 casement windows with an equal number of associated top lights. These were observed daily, and weather conditions, including temperature, wind speed, wind direction, and hours of sunshine, were recorded. As with dwellings, the most significant independent variable was found to be outdoor air temperature, although wind speed and the hours of sunshine on the day of observation also influenced window opening. Fig. 1 illustrates Pallot's results and shows the monthly mean percentage of windows open each day with outdoor air temperature.

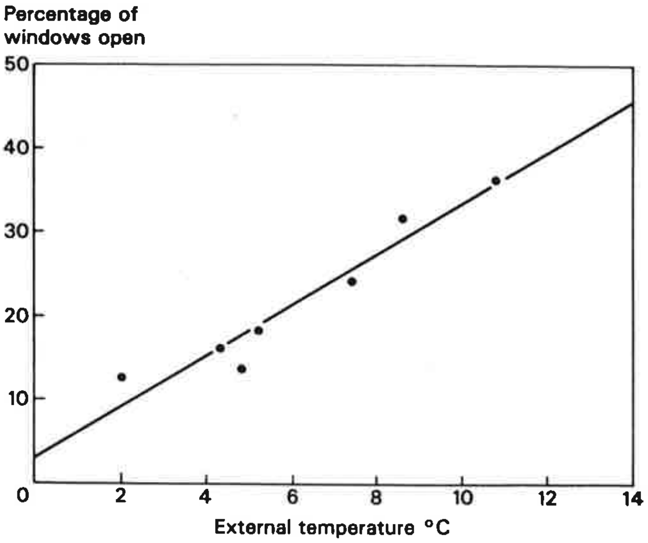


Fig. 1. The variation with external dry bulb temperature of the mean monthly percentage of windows open, for a London office building during the 1951-52 heating season, from results given by Pallot 1962.
(regression line: ———— $y = 3.0x + 3.3$ ($r = 0.98$))

3 The current survey

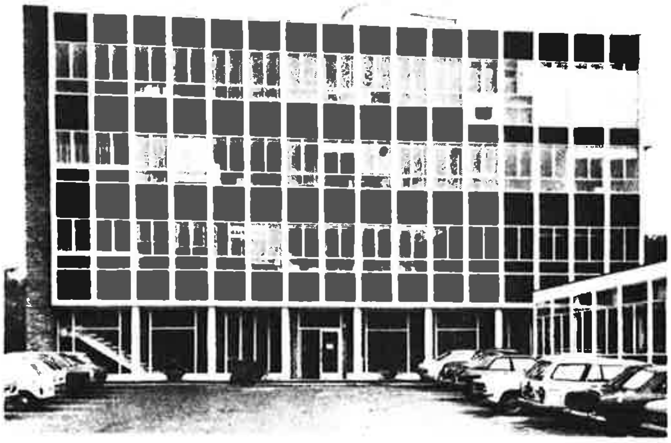
Five buildings were chosen for the survey. For convenience all were situated at the Building Research Establishment site at Garston, approximately 30 miles north of London. Each building consists primarily of small offices for one or two people but also includes, in some cases, a small number of offices with larger occupancy, as well as rooms for other purposes. The buildings are identified as A, B, C, D and E, and brief details are listed in Table 1. They are typical of the general stock of small, naturally ventilated office buildings. All are heated by low-temperature hot water distributed to radiators within the rooms. Automatic control is provided by external temperature compensators, which reduce the supply temperature of the water as outdoor air temperature rises. The heating systems are not zoned, and the same energy inputs are available to each side of the building unless occupants make use of the manual control valves associated with each radiator. Buildings A, D and E have separate compensators, but buildings B and C are linked to the same unit. Fig. 2 shows a general view of each building. Fig. 3 is a site plan showing the positions and orientation of the buildings and indicating the facades that were observed.

The survey was carried out over a period of 13 weeks from 26 February to 25 May. Each chosen facade was photographed twice each day between 11.00 and 11.30 and between 14.00 and 14.30. The resulting 35 mm transparencies, when projected, enabled those windows that were open to be identified. One hundred and ninety-six

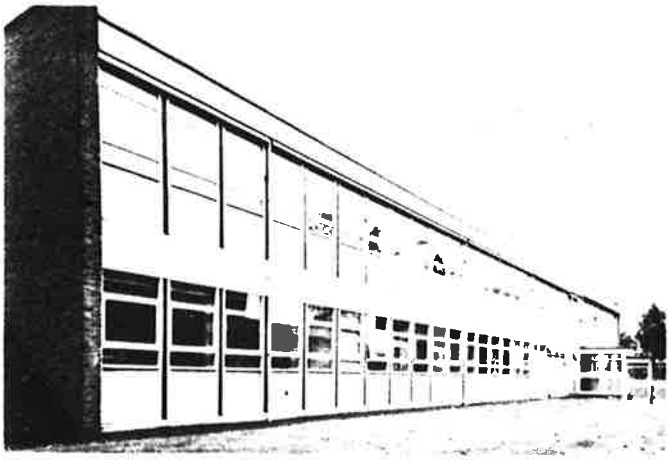
Table 1. Details of Buildings

Building	A	B	C	D	E
Construction	Medium Weight	Light to Medium Weight	Lightweight	Medium Weight	Heavyweight
	Concrete frame Curtain walling with cavity filled brick ends	Steel frame with concrete casing Brick external walls	Light steel frame Curtain walling	Concrete frame Curtain walling	Load bearing brick external walls
	Block partitions	Block partitions	Lightweight partitions	Block partitions	Block partitions
	Solid concrete floors	Precast concrete U-section floors	Timber floors	Solid concrete floors	Solid concrete floors
Heating	All buildings have hot water radiators fed by a calorifier in a plant room; overall water temperature is controlled by external temperature sensors. All radiators have individual valve controls.				
Windows	Side-hung casements with a few small louvres in larger offices	All side-hung casements	Top-hung windows plus small louvres on first floor of south-east face	Small and large top-hung windows	All horizontally pivoted windows (pivoted very near top, so classed as top-hung)
Aspects	076 166 256 346	099 189 279	099 279	068 248	076 256

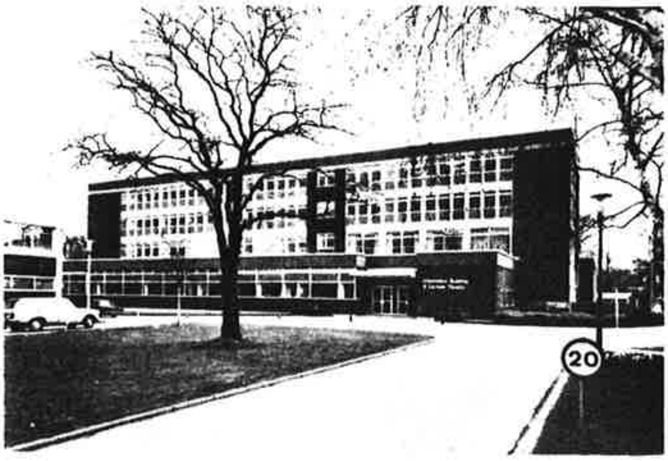
(i) Building A



(ii) Building B



(iii) Building C



(iv) Building D

(v) Building E

Fig. 2. General views of the five naturally ventilated office buildings used for the survey.

offices were identified and used in the survey, and the following were recorded for each office:

the number of large windows that were wide open,
the number of large windows that were slightly open,
the number of small windows that were wide open, and
the number of small windows that were slightly open.

In this context, large windows were the main windows, and small windows were the additional openable windows present in buildings C and D. 'Slightly' open was defined as being open to the first fixed position of the window stay. 'Wide' open was defined as any position beyond that. Office occupants were asked to keep a record of the mornings and afternoons during which the office was occupied for a period of at least one hour. This record was collected each week, and only those offices that contained an occupant were included within the subsequent analysis.

For each period of observation, morning and afternoon, external air temperature, mean wind speed and wind direction were recorded locally. General weather conditions were classified as follows:

Sunny (mainly clear sky).
Sun/cloud (approximately 50 per cent overcast).

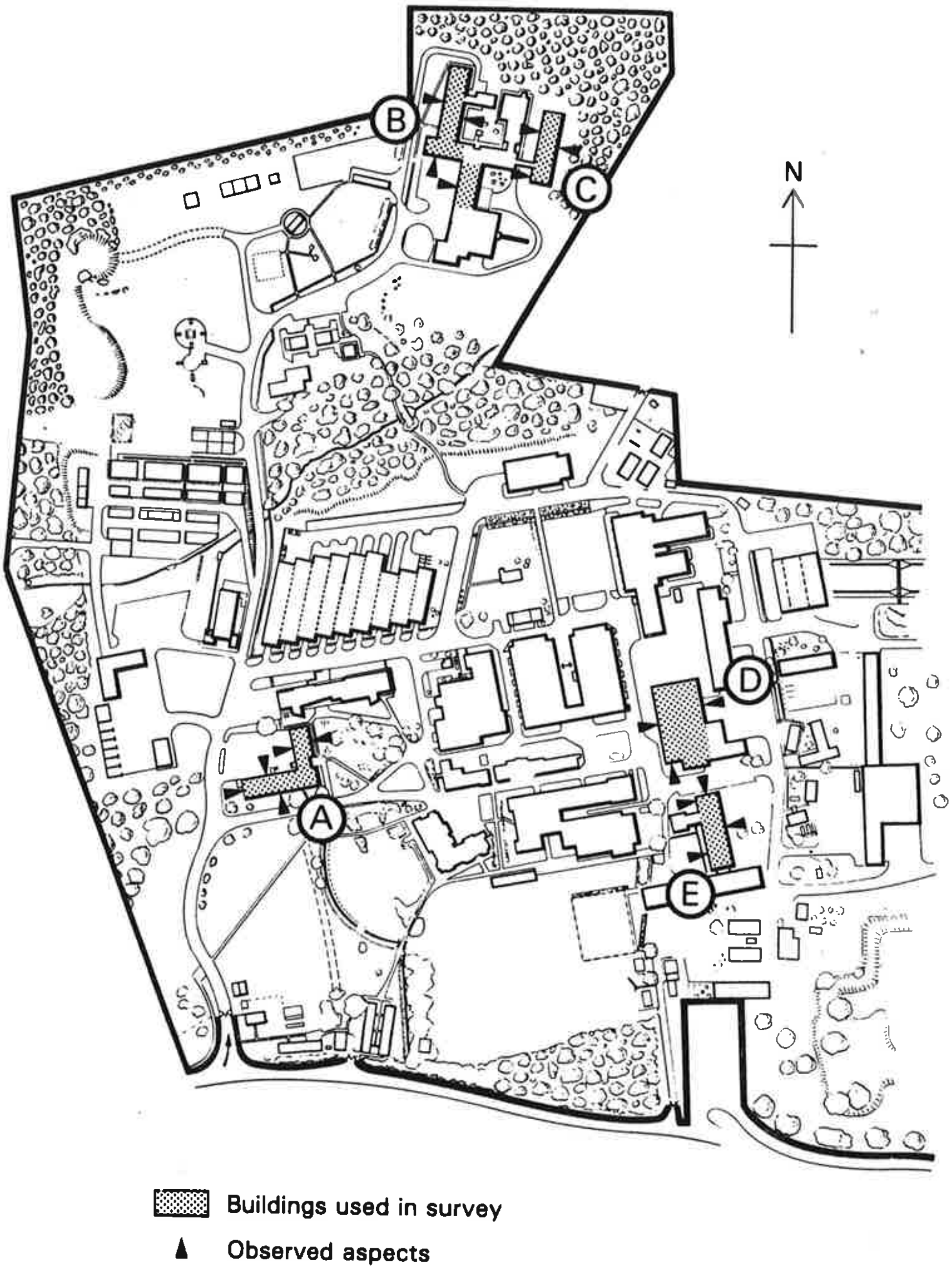


Fig. 3. Site plan showing the location and orientation of the five office buildings.

Cloud (mainly overcast sky).
Light rain.
Rain.
Snow.
Sleet.

Subsequent sunshine records were analysed, and the total daily cumulative hours of sunshine, prior to the period of observation, were recorded. In ten cases (four mornings and six afternoons) these were not available. The recorded data and the window observations were coded and stored on a computer for subsequent analysis, using a standard statistical package of programs[9].

After the three-month period of observations had been completed, each occupant was invited to complete a brief questionnaire. Appendix 1 shows the questions relating to window-opening behaviour. A total of 242 forms was distributed, of which 210 were returned, corresponding to 174 of the 196 offices surveyed. The distribution of respondents by age and sex is shown in Table 2; 139 returns were from occupants of single-person offices, 50 from two-person offices, and the remaining 21 from offices with three or more occupants.

Table 2. Distribution of occupants by age and sex

Age Group	Male (per cent)	Female (per cent)	Total (per cent)
Under 25	15 (10.9)	13 (22.8)	28 (14.3)
26-35	39 (28.3)	8 (13.8)	47 (24.0)
36-45	34 (24.6)	16 (27.6)	50 (25.5)
46-55	30 (21.7)	13 (22.4)	43 (21.9)
56-65	20 (14.5)	8 (13.8)	28 (14.3)
Total	138 (70.4)	58 (29.6)	196 (100)

No. of missing responses = 14.

4 Results

A total of 90 sets of observations was obtained (45 morning, 45 afternoon). Appendix 2 lists these together with the recorded weather data. The number of windows open is expressed in two ways:

(1) as the number of occupied rooms with one or more windows open, expressed as a percentage of the total number of occupied rooms;

(2) as the number of open windows expressed as a percentage of the total number of windows in occupied rooms. In this case, a further division may be made between large and small windows.

Fig. 4 shows the percentage of rooms with one or more windows open against external air temperature. A strong correlation ($r = 0.82$; $p < 0.001$) is evident. A stepwise multiple correlation analysis was therefore carried out against the following four weather-related variables:

(1) External dry-bulb temperature (°C).

(2) Wind speed (m/s).

(3) Hours of sunshine preceding the observation (h).

(4) A dummy variable representing precipitation (taking the value 1, if rain or any other form of precipitation occurred during the observation period, and 0 otherwise).

The results of this analysis are given in the first part of Table 3. External air temperature accounted for 76 per cent of the observed variance, the effect of sunshine for an additional 8 per cent, and wind speed, 4 per cent. The remaining term made a negligible contribution. Also shown in Table 3 is a similar analysis with the percentage of open windows as the dependent variable. As would be expected, the results are close, with a similar contribution by the independent variables to the variance. The contribution of sunshine to the number of open windows is illustrated by Fig. 5 in which results for sunny and cloudy conditions only, and with wind speed less than 5 m/s, are plotted.

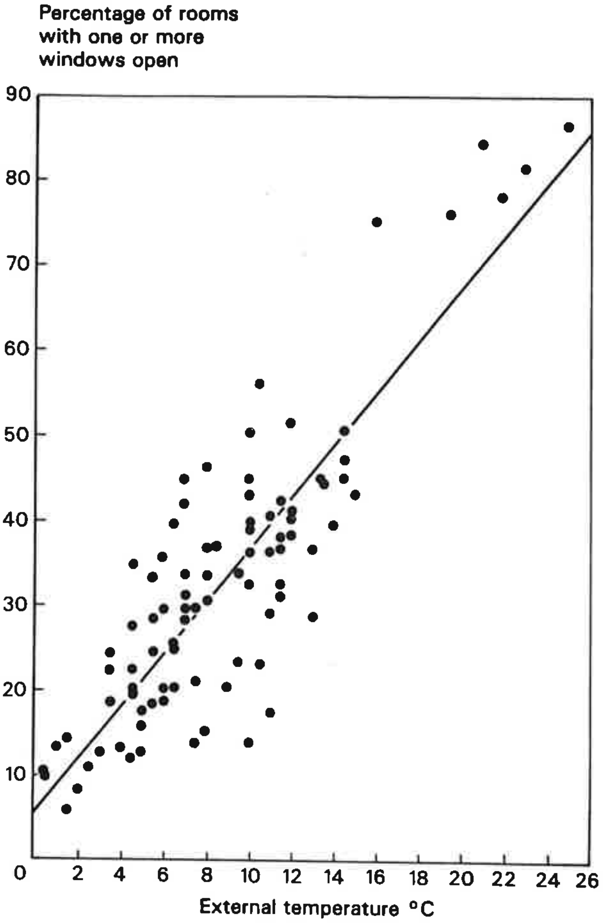


Fig. 4. The variation of the percentage of occupied rooms, with one or more windows open, with external dry bulb temperature.
(regression line: ———— $y = 3.1x + 5.1$ ($r = 0.87$))

Table 3. Stepwise linear multiple regression analysis of window opening with weather parameters (196 offices over 80 half-day periods)

Dependent Variable	Independent Variables						
	Constant	External air temp. (°C)	Hours of sunshine (h)	Wind speed (m/s)	Precipi-tation (—)	r	r^2
Percentage of occupied rooms with one or more windows open	5.1	3.1				0.87	0.76
	2.7	2.7	2.4			0.92	0.84
	15.8	2.4	2.3	−2.3		0.94	0.88
	16.1	2.5	2.3	−2.3	−0.6	0.94	0.88
Percentage of all windows in occupied rooms which are open	−3.2	2.0				0.86	0.75
	−4.4	1.7	1.3			0.90	0.81
	1.6	1.6	1.3	−1.0		0.91	0.83
	3.3	1.7	1.3	−1.0	−3.0	0.92	0.84
Number of large windows opened wide as a percentage of all windows in occupied rooms	−5.6	1.7				0.84	0.71
	−6.7	1.5	1.1			0.88	0.77
	−1.1	1.4	1.0	−1.0		0.89	0.79
	0.6	1.5	1.1	−1.0	−3.0	0.90	0.80
Number of large windows slightly open plus number of small windows open as percentage of all windows in occupied rooms	2.5	0.27				0.76	0.58
	2.2	0.23	0.24			0.81	0.66
	2.7	0.22	0.24	−0.1		0.81	0.67

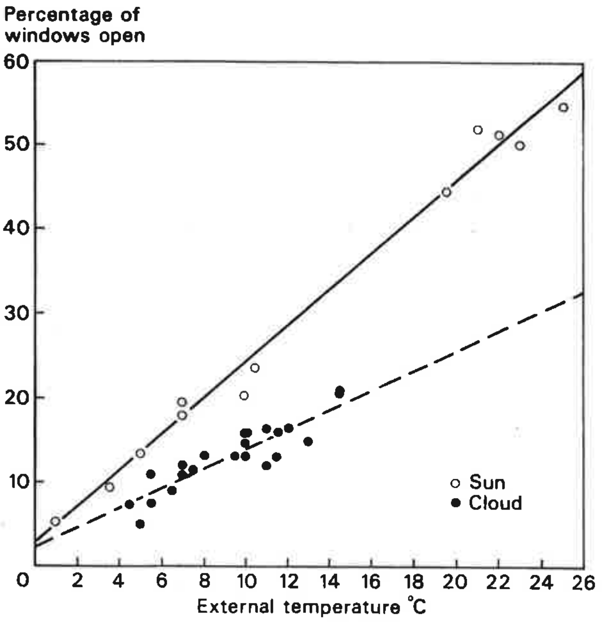


Fig. 5. The variation of the percentage of all windows open with external dry bulb temperature, for days with sun or cloud and with wind velocity less than 5 m/s.
(regression lines:
sun; ———— $y = 2.2x + 2.9$ *(*$r = 0.99$*))*
cloud; – – – – – $y = 1.2x + 2.2$ *(*$r = 0.90$*))*

Table 3 also contains the results of a stepwise multiple linear regression on two other variables. These were obtained by dividing the number of open windows into two groups: (1) large windows fully open and (2) the remaining open windows (large windows slightly open and small windows either slightly or wide open). This was done with the intention of differentiating between large areas of opening and small areas of opening. It is apparent that the use of 'small' openings is much less closely associated with the weather-related variables than the use of the 'large' openings. The use of large openings increases approximately six times faster with external air temperature and four times faster with hours of sunshine. The influence of wind speed on the small openings is also substantially lower.

A measure of the variability in window opening between buildings is given in Table 4. The number of occasions on which a room has one or more windows open may be expressed as a percentage of the total number of possible occasions. This percentage for each room has been averaged for all the rooms on each facade of the five buildings and overall for each building. These values give an indication of the relative differences between buildings, since the observations were made over the same period for each building. The overall mean values show that windows were opened most frequently in Building C (48.4 per cent of occasions) and least often in Buildings A and B (25.3 per cent and 25.0 per cent of occasions, respectively). Independently of building, windows in rooms on facades facing east tend to be opened more frequently than those on west-facing facades. Except for the east-facing facade of Building B, rooms on all facades tend to be opened slightly more frequently in the afternoon than the morning.

Tables 5(a) to 5(g) give the results of the questionnaire survey. Respondents were asked to differentiate between summer and winter when preparing their replies. In summer, a substantial majority (75.1 per cent) reported that they opened windows often or all the time, whereas only 4.4 per cent rarely or never opened windows. This accords with the response to question (2), which showed a bias to the warm end of the scale, with 30.9 per cent claiming to be either too warm or much too warm. In winter, 5.5 per cent of respondents claimed to be too warm or much too warm, and a further 21.0 per cent were comfortably warm, with the response being fairly evenly distributed about the centre of the scale. Nevertheless 18.7 per cent claimed to have windows open often or all of the time. A substantial number of respondents (56.5 per cent) kept doors to their rooms open in summer. Even in winter, 44.4 per cent retained open doors. This is important since closed internal doors tend to inhibit natural cross-ventilation.

In both summer and winter, the reason given most frequently for opening windows was for fresh air possibly because this is the most general of the suggested responses with no specific relation to thermal climate or indoor air quality. In winter the replies tend to be more weighted to those reasons that relate more closely to air quality, although 18.1 per cent cite the need to keep the room cool.

Table 4. Average percentage of occasions on which a room had one or more windows open

Building		Aspect									
		068	076	099	166	189	248	256	279	346	Mean
	a.m.		33.3		13.9			31.4		13.2	25.2
A	p.m.		33.8		19.0			41.0		16.6	27.9
	mean		33.5		16.5			36.2		14.9	26.6
	a.m.			29.9		25.0			17.3		21.2
B	p.m.			25.1		30.4			22.5		25.0
	mean			27.5		27.7			19.9		23.1
	a.m.			54.0					34.0		44.5
C	p.m.			60.4					45.0		53.2
	mean			57.2					39.5		48.9
	a.m.	40.7					28.5				34.0
D	p.m.	42.0					30.1				35.4
	mean	41.4					29.3				34.7
	a.m.		36.8					18.3			28.2
E	p.m.		43.0					27.7			34.7
	mean		39.9					23.0			31.5

Table 5. (a) Question 1—How often are the windows in this room open?

	Summer (per cent)	Winter (per cent)
Never	1 (0.5)	21 (10.1)
Hardly ever	8 (3.9)	79 (38.0)
Occasionally	41 (20.0)	68 (32.7)
Often	124 (60.5)	34 (16.3)
All of the time	30 (14.6)	5 (2.4)
Don't know	1 (0.5)	1 (0.5)

(b) Question 2—Use one of the following to describe how this room usually feels

	Summer (per cent)	Winter (per cent)
Much too warm	7 (3.6)	2 (1.0)
Too warm	53 (27.3)	9 (4.5)
Comfortably warm	54 (27.8)	42 (21.0)
Comfortable	73 (37.6)	85 (42.5)
Comfortably cool	7 (3.6)	19 (9.5)
Too cool	0 (—)	31 (15.5)
Much too cool	0 (—)	11 (5.5)

(c) Question 3—Is the door to this room usually kept open/closed?

	Summer (per cent)	Winter (per cent)
Open	113 (56.5)	91 (44.4)
Closed	87 (43.5)	114 (55.6)

(d) Question 4—If you open your window(s) is it for any of the following reasons?

	Summer (per cent)	Winter (per cent)
For fresh air	155 (73.8)	109 (51.0)
If the room is stuffy	63 (30.0)	82 (39.0)
To stop room getting stale	56 (26.7)	63 (30.0)
To get rid of tobacco smoke	39 (18.1)	45 (21.4)
To keep room cool	155 (73.8)	38 (18.1)
To get rid of smells	17 (8.1)	24 (11.4)
To stop condensation	0 (—)	3 (1.4)
Other	1 (0.5)	1 (0.5)

(e) Question 5—If you close your window(s) is it for any of the following reasons?

	Summer (per cent)	Winter (per cent)
To keep room warm	58 (27.6)	150 (71.4)
To keep out noise	127 (60.5)	91 (43.3)
To prevent draughts	78 (37.1)	89 (42.4)
To keep out rain	62 (29.5)	53 (25.2)
For security	26 (12.4)	25 (11.9)
To keep out dust and dirt	12 (5.7)	6 (2.9)
For privacy	3 (1.4)	4 (1.9)
Other	5 (2.4)	4 (1.9)

(f) Question 6—Are there any particular times of the day when you open your window(s)?

	Summer (per cent)	Winter (per cent)
Beginning of the day	90 (42.9)	53 (25.2)
During morning	41 (19.5)	29 (13.3)
Before lunch	5 (2.4)	4 (1.9)
During lunchtime	8 (3.8)	6 (2.9)
After lunch	32 (15.2)	15 (7.1)
During afternoon	39 (18.6)	17 (8.1)
End of day	1 (0.5)	2 (1.0)
Other	1 (0.5)	1 (0.5)
None	37 (17.6)	53 (25.2)

(g) Question 7—Are there any particular times of the day when you close your window(s)?

	Summer (per cent)	Winter (per cent)
Beginning of the day	4 (1.9)	4 (1.9)
During morning	5 (2.4)	7 (3.3)
Before lunch	7 (3.3)	5 (2.4)
During lunchtime	3 (1.4)	4 (1.9)
After lunch	3 (1.4)	2 (1.0)
During afternoon	7 (3.3)	9 (4.3)
End of day	137 (5.2)	109 (51.9)
Other	1 (0.5)	0 (0.0)
None	33 (15.7)	42 (20.0)

This proportion is similar to the number who claimed to open windows often or all the time. The most popular reason for opening windows in summer is the need to keep the room cool, which accords with responses to questions 1 and 2. Condensation was given as a reason by only three respondents.

Understandably, the major reason given for closing windows in winter was to maintain warmth. The need to keep out noise was also given as a major reason for closing windows in both summer and winter. The immediate environment of the site is a mixture of open country and suburban development; there is, however, a highway that runs within 100 m of the western edge, which may account for noise being cited so frequently. However, the proportions citing any reason for closing windows does not necessarily reflect the actual frequency of the action. The response to question 7 indicates that the most people close their windows at the end of the day, rather than at any other time. The time of opening, however, given in response to question 6, is much more evenly spread throughout the day. This would suggest that once opened, windows are rarely closed until the room is finally vacated at the end of the working day.

5 Discussion

The preceding analysis of observed window-opening behaviour led to two regression equations, one for 'large' openings, the other for 'small' openings. The regression coefficients are listed in Table 3. Examination of these coefficients indicates that they are significantly different, and it is suggested that these provide evidence for two distinct modes of window use. In the first, windows are used by occupants to provide a small open area and this mode is relatively independent of the main weather-related variables. In the second, windows are used to provide a large open area; this mode is closely tied to outdoor air temperature and hours of sunshine.

A possible explanation is that the 'small' opening mode is related to the need to maintain satisfactory indoor air quality, which would be expected to be largely independent of external weather conditions. Further, it is suggested that the 'large' opening mode is likely to be related to the need to maintain internal temperature at a level the occupant finds comfortable. This explanation is consistent with the high degree of dependence of the 'large' opening mode on external temperature and hours of sunshine, since these factors have a major effect on the internal thermal environment.

In principle, for the buildings considered in this study, any rise in the temperature of the external air should be compensated for by a reduction of the temperature of the circulating water and, consequently, in the heat input to rooms from the radiator. This depends upon the accurate setting of the compensator and the efficient functioning of the heating system. If this is not the case, then over- or underheating may occur. In the former case, the occupant is faced with two alternatives, either to reduce the flow through the radiator by using the manual control valve or to increase the ventilation rate by opening a window. The effect of the latter action will probably be more immediate and therefore more acceptable to the occupant. Similarly, hours of sunshine will be closely related to solar gain. In the case of these buildings, the heating control system does not compensate for solar gain, and the occupant is faced with a straight choice between manual control and increased ventilation by window opening.

Although the results represented by Table 4 are aggregates of all five buildings, there is a clear indication that windows in some, if not all, of the buildings are in excess of actual fresh air requirements and therefore represent an energy loss. For any given building, the relationship between window opening and the main weather-related variables will depend upon the nature of the heating system and its controls and building characteristics that include in particular the glazed area and orientation. Individual occupants will also vary in their response to changes in internal temperature. The values of the coefficients obtained by the regression analysis, therefore, have no intrinsic value but nevertheless may be used to illustrate the magnitude of the possible excess ventilation rate due to window opening. For this purpose, only the simple regression of large window opening against external temperature will be used. Appendix 5 describes a simple method, using this equation, to estimate the excess ventilation rate for a typical naturally ventilated office building. For any specific case, the distribution of the opened windows would be important, but for present purposes two extremes are considered:

(1) The windows are equally distributed over to opposing faces of the building. Resistance to internal flow is assumed to be negligible. This approximates to optimum cross-ventilation.

(2) The windows are equally distributed as above, but each room containing a window is effectively sealed from the remainder of the building. There is, therefore, no cross-ventilation, and all air exchange must take place across the windows in one wall. Suitable mechanisms and methods for calculating this "single-sided" ventilation are set out in Warren[10].

Fig. 6 shows the results for the two extreme conditions based on the assumptions set out in Appendix 3. The minimum fresh air requirement for air-conditioned private offices set out in the CIBS Guide[11] is 1.3 l/s m^2 floor area. Depending upon which of the above cases is taken, this is exceeded in the example under consideration when the external temperature is above 4.5 °C or 6.5 °C. Hence, for a substantial proportion of the heating season, ventilation rates due to window opening will be above the minimum fresh air requirement and incurring unnecessary energy consumption.

It must be emphasised that the values given above should only be taken as an indication of the degree to which natural ventilation is in excess of requirements during the heating season. More detailed studies are required to examine the complex interaction between human behaviour, building characteristics, and heating system performance in order to develop methods that take into account the additional heat loss due to window opening for incorporation in calculations for predicting building performance and energy consumption. As a start, the results described in this paper are being analysed on a building-by-building basis in conjunction with estimates of the thermal performance of the individual buildings. Further field measurements of window opening behaviour are also being undertaken.

6 Conclusions

(1) The window-opening behaviour of occupants in 196 small offices situated in five naturally ventilated buildings has been observed over a range of weather conditions. Window opening occurred over the whole range and was found to be strongly correlated with weather, confirming results found by other workers in dwellings and by Pallot[8] in an office building. The main independent variable was found to be outdoor air temperature, but solar gain, represented by hours of sunshine, and wind speed, also had important effects.

(2) It is suggested that two modes of window opening occur. In the first, windows are opened by a small amount to satisfy indoor air quality requirements. In the second, windows are opened to give large openings and higher rates of natural ventilation in order to control internal temperature.

(3) The extent to which windows are used in the heating season to control internal temperature will depend upon a range of factors, including the thermal characteristics of the building structure, the type of heating system, and the methods available for its control. It is suggested that further work should be carried out to examine the interaction of these factors with occupant behaviour.

(4) On the basis of the results of the survey, an estimate was made of the ventilation rate arising from window opening, and this was shown to be well above basic fresh-air requirements. Consideration should be given to developing methods to take into account the additional heat loss incurred by excess ventilation for use in building design and performance calculations.

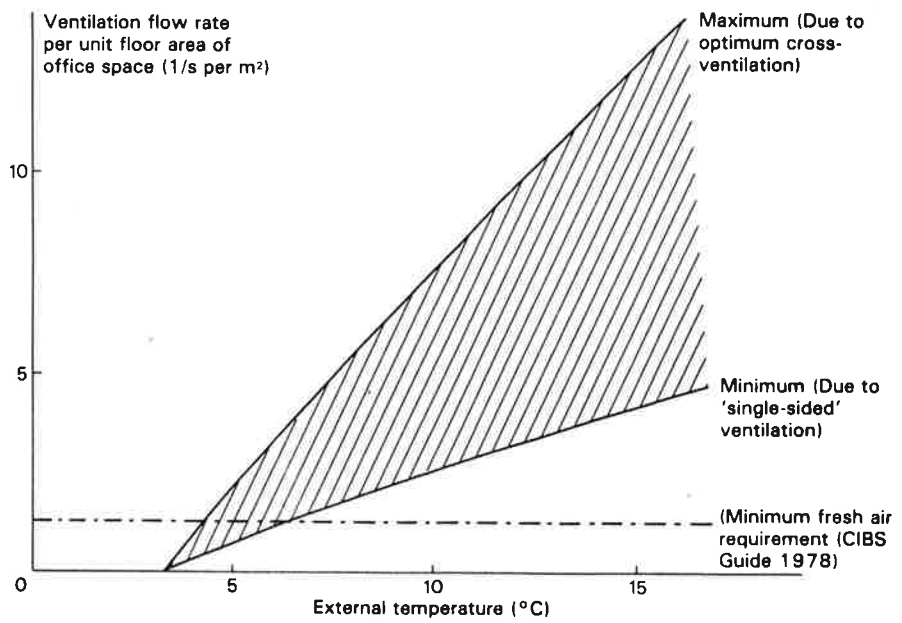


Fig. 6. Estimated range of ventilation due to large windows opened wide as a function of external dry bulb temperature.

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APPENDIX 1

Questions relating to Window-Opening Behaviour

Occupants of the five buildings were asked to complete a qustionnaire that included the following questions in relation to window-opening behaviour:

1. How often are the windows in this room open? (please tick)

	Summer	Winter
Never	☐	☐
Hardly ever	☐	☐
Occasionally	☐	☐
Often	☐	☐
All the time	☐	☐
Don't know	☐	☐

2. Use one of the following to describe how this room usually feels (please tick)

	Summer	Winter
Much too warm	☐	☐
Too warm	☐	☐
Comfortably warm	☐	☐
Comfortable	☐	☐
Comfortably cool	☐	☐
Too cool	☐	☐
Much too cool	☐	☐

3. Is the door to this room usually kept (please tick)

	Summer	Winter
Open?	☐	☐
Shut?	☐	☐

4. If you open your window(s) is it for any of the following reasons? (please tick if 'yes')

	Summer	Winter
For fresh air	☐	☐
To keep room cool	☐	☐
To stop room getting stale	☐	☐
If the room is stuffy	☐	☐
To stop condensation	☐	☐
To get rid of smells	☐	☐
To get rid of tobacco smoke	☐	☐
Others (please state)	☐	☐

5. If you close your window(s) is it for any of the following reasons? (please tick if 'yes')

	Summer	Winter
To keep room warm	☐	☐
To keep out noise	☐	☐
To keep out dust and dirt	☐	☐
To prevent draughts	☐	☐
To keep out rain	☐	☐
For privacy	☐	☐
For security	☐	☐
Others (please state)	☐	☐

6. Are there any particular times of day when you open your window(s)? (please tick)

	Summer	Winter
Beginning of day	☐	☐
During morning	☐	☐
Before lunch	☐	☐
During lunchtime	☐	☐
After lunch	☐	☐
During afternoon	☐	☐
End of day	☐	☐
Other (please state)	☐	☐
None	☐	☐
Don't know	☐	☐

7. Are there any particular times of day when you close your window(s)? (please tick)

	Summer	Winter
Beginning of day	☐	☐
During morning	☐	☐
Before lunch	☐	☐
During lunchtime	☐	☐
After lunch	☐	☐
During afternoon	☐	☐
End of day	☐	☐
Other (please state)	☐	☐
None	☐	☐
Don't know	☐	☐

APPENDIX 2

Summary of results

(a) Morning observations

Date	Weather	External temp. (°C)	Wind direction (degrees)	Wind speed (m/s)	Hours of sunshine before observation period	No. of occupied rooms	Percentage of rooms with one or more windows open	Percentage of windows open		
								Large	Small	Total
26/2	sun	1.0	190	3	3.0	165	13.3	3.8	12.1	5.4
27/2	cloud	4.0	190	7	0.5	159	13.2	4.4	8.2	5.1
28/2	rain	3.0	300	7	0	158	12.7	3.5	10.5	4.9
1/3	sun	4.5	250	5	4.0	151	22.5	8.8	10.5	9.1
2/3	cloud	10.0	230	6	0	150	14.0	4.8	11.0	6.0
12/3	cloud	8.0	250	8	1.4	156	15.3	5.8	6.1	5.8
14/3	snow	2.5	020	6	0	148	10.9	3.2	7.5	4.1
15/3	snow	3.5	360	8	0	142	9.9	3.3	5.7	3.8
16/3	snow	1.5	340	5	0	140	5.7	2.8	0	2.3
19/3	cloud	4.5	050	4	—	137	19.7	6.5	11.1	7.5
20/3	cloud	6.5	180	3	—	142	20.4	8.7	9.5	8.9
22/3	cloud	5.0	230	4	—	141	12.7	4.8	4.7	4.8
23/3	sun	4.5	310	2	—	141	34.8	14.8	8.1	13.4
26/3	sleet	2.0	220	8	0	145	8.3	2.1	3.0	3.3
27/3	cloud	6.5	220	7	3.2	140	25.0	8.2	13.8	9.4
28/3	cloud	4.5	280	7	2.2	140	20.0	6.3	10.0	7.1
30/3	cloud	5.0	350	6	0	132	15.9	4.2	11.0	5.7
9/4	rain	7.5	060	2	0	145	13.8	5.6	7.6	6.0
10/4	sun	13.4	150	6	1.3	144	45.2	19.2	10.9	17.4
11/4	cloud	11.0	150	3	0	144	29.2	12.2	11.2	12.0
12/4	rain	3.0	160	6	1.0	117	20.5	8.4	7.0	8.1
17/4	cloud	5.5	350	4	3.0	129	28.7	11.5	8.6	10.9
18/4	sun	7.0	020	2	1.0	138	42.0	21.7	7.8	19.4
19/4	sun/cloud	12.0	210	4	0.4	138	41.3	19.0	18.5	17.4
20/4	cloud	9.5	290	4	0.6	130	33.8	12.7	14.3	13.1
23/4	cloud	10.5	220	7	0.4	150	23.3	8.1	13.5	9.2
24/4	rain	7.0	330	2	1.9	147	31.3	11.6	12.8	12.0
25/4	cloud	7.0	280	6	2.4	144	28.5	10.1	15.4	11.1
26/4	cloud	8.0	340	5	2.0	140	30.7	11.8	18.1	12.9
27/4	cloud	8.0	340	3	1.3	130	33.8	13.4	12.3	13.2
28/4	sun/cloud	8.5	280	4	4.7	148	37.2	15.3	17.0	15.7
1/5	cloud	7.0	210	3	0.3	145	29.7	18.2	14.1	11.0
2/5	sun/cloud	4.5	290	5	3.0	141	27.7	10.5	13.5	11.1
3/5	sun/cloud	6.5	270	2	4.6	141	39.7	16.4	12.2	15.6
4/5	sun/cloud	6.0	320	2	4.4	134	35.8	15.4	11.2	14.5
8/5	cloud	11.5	230	3	0	149	36.9	17.3	11.6	16.0
9/5	cloud	10.0	310	3	2.0	151	36.4	16.6	13.3	15.9
13/5	cloud	11.0	140	4	0	140	43.7	18.1	9.6	16.4
14/5	sun	19.5	180	3	4.7	150	76.0	48.5	29.1	44.7
15/5	sun	22.0	180	2	4.2	137	78.1	57.4	29.1	51.4
16/5	sun	21.0	210	4	4.5	140	84.3	57.2	33.3	52.0
21/5	sun/cloud	12.0	200	5	2.5	152	38.2	17.1	12.5	16.1
22/5	cloud	11.5	210	3	1.7	132	31.1	13.1	11.4	12.8
23/5	cloud	11.5	230	6	2.5	126	32.5	13.5	10.6	12.8
25/5	sun/cloud	12.0	230	4	4.7	128	51.6	22.7	14.7	21.1

APPENDIX 2

Summary of results

(b) Afternoon observations

Date	Weather	External temp. (°C)	Wind direction (degrees)	Wind speed (m/s)	Hours of sunshine before observation period	No. of occupied rooms	Percentage of rooms with one or more windows open	Percentage of windows open		
								Large	Small	Total
26/2	sun	3.5	210	4	5.3	159	24.5	8.3	11.4	9.3
27/2	sun	6.5	180	6	2.9	159	25.2	9.6	11.4	9.9
28/2	cloud	5.2	290	5	0.6	148	17.6	5.7	10.0	6.6
1/3	cloud	4.5	250	5	6.3	148	22.3	8.9	10.3	9.2
2/3	cloud	11.0	230	6	0	143	17.5	6.4	11.0	7.3
12/3	cloud	9.5	260	7	4.1	144	23.6	9.8	8.0	8.8
14/3	snow	3.5	020	5	0	144	18.7	6.8	8.0	7.1
15/3	snow	0.5	360	6	—	146	18.3	3.5	4.3	3.7
16/3	snow	1.5	340	5	—	132	14.4	6.1	3.8	5.7
19/3	cloud	5.5	070	4	—	146	18.5	7.7	7.8	7.5
20/3	rain	8.0	210	7	—	90	36.7	18.8	5.6	9.0
22/3	sun	5.5	240	6	—	139	24.5	9.2	9.2	9.2
23/3	sun	7.0	300	2	—	134	44.8	19.4	12.8	13.0
26/3	rain	4.5	240	8	0	142	12.0	3.4	10.7	4.9
27/3	sun	7.5	230	6	5.1	142	21.1	6.9	11.9	7.9
28/3	cloud	6.0	280	7	2.5	133	18.8	5.7	10.4	6.8
30/3	cloud	6.0	350	5	0	124	20.2	6.3	9.6	7.0
9/4	cloud	10.0	100	2	0.8	144	32.6	13.9	10.9	13.2
10/4	cloud	14.5	150	4	3.2	140	50.7	22.5	11.6	20.3
11/4	sun/cloud	14.0	150	5	1.6	133	39.8	16.4	12.4	15.5
17/4	cloud	7.5	350	4	3.0	128	29.7	12.2	9.6	11.7
18/4	sun	10.5	340	2	4.0	130	56.2	29.9	10.9	26.6
19/4	cloud	12.0	230	4	1.5	132	40.2	17.7	10.5	16.3
20/4	cloud	11.0	280	5	1.1	121	36.4	14.0	13.1	13.8
23/4	sun	13.0	210	6	1.5	142	28.9	10.8	14.1	11.5
24/4	cloud	10.0	340	3	2.0	142	38.7	14.8	14.8	14.8
25/4	cloud	10.0	280	6	3.6	131	45.0	21.8	15.4	17.9
26/4	sun/cloud	10.0	340	4	3.5	130	43.1	19.3	14.5	18.4
27/4	cloud	10.0	330	3	1.9	123	39.8	16.0	15.1	15.8
30/4	sun/cloud	10.5	280	6	7.3	143	40.6	16.3	18.9	16.8
1/5	rain	6.0	100	2	0.3	142	29.6	11.6	12.6	10.8
2/5	cloud	7.0	260	3	4.7	140	33.6	10.9	13.0	12.1
3/5	sun/cloud	8.0	270	4	6.8	138	46.4	19.5	12.1	17.9
4/5	rain	5.5	270	5	6.2	129	33.3	12.5	10.6	12.1
8/5	cloud	14.5	240	3	1.3	149	47.0	22.5	13.0	20.5
9/5	sun/cloud	14.5	300	3	3.8	144	45.1	21.5	15.5	20.3
10/5	cloud	13.0	160	4	0.2	134	36.6	16.5	8.6	14.8
14/5	sun	23.0	190	3	7.7	146	81.5	55.7	28.2	50.1
15/5	sun	25.0	210	1	7.2	133	86.5	62.1	28.1	54.7
16/5	cloud	16.0	250	5	7.6	133	75.2	47.6	21.8	42.0
21/5	rain	11.0	210	4	4.7	142	38.0	15.4	13.6	15.0
22/5	cloud	15.0	200	5	3.9	134	43.3	19.6	15.5	18.7
23/5	sun/cloud	13.5	—	6	5.2	133	44.4	19.0	11.6	17.3
24/5	sun	19.0	140	1	3.6	133	50.4	21.7	14.1	28.1
25/5	sun/cloud	11.5	210	4	6.9	118	42.4	18.5	15.4	17.9

APPENDIX 3

Ventilation rate due to window opening

Introduction

The purpose of this appendix is to set out a method for estimating the ventilation rate resulting from the variation in window opening discussed in the main body of the paper. The intention is to indicate orders of magnitude, rather than provide precise values.

A simple building model is assumed. This consists of a two-dimensional building with the open area resulting from the use of windows equally and uniformly distributed across each of the two facades. Two extreme conditions will be considered:

Cross-ventilation:

In this case, the resistance to flow through the building is assumed to be zero. This approximates the situation in a real building with all internal doors open and no obstructing partitions.

'Single-sided' ventilation:

In this case, rooms containing windows are assumed to be effectively sealed from the rest of the building. All air exchange takes place through the window(s) on the one external wall. This approximates to the situation in a real building with all internal doors closed. Warren[10] discusses the mechanisms of natural ventilation appropriate to this case.

For each of these two cases, formulae will be set out for the calculation of natural ventilation due to (1) wind and (2) stack effect. These will then be combined, using a simple quadrature expression to give an expression for the two acting together. The use of a quadrature expression has been found to be appropriate for the same purpose when predicting infiltration (Warren[12]).

Cross-ventilation

Wind

The ventilation flow rate, Q_W(m^3/s), resulting from an area of opening, A(m^2), is given by,

$$Q_W = C_D.A.U.(\triangle C_p)^{1/2}/2\sqrt{2} \quad (1)$$

where:

C_D = Discharge coefficient for a sharp-edged opening (= 0.61).
U = Wind speed at a height equal to that of the building (m/s).
$\triangle C_p$ = The difference between wind pressure coefficients at the windward and leeward faces of the building.

Stack

The ventilation flow rate, Q_S(m^3/s), resulting from a temperature difference, $\triangle$T (°C), between indoor and outdoor air is given by,

$$Q_S = C_D.A.(g.H.\triangle T/\bar{T})^{1/2}/3 \quad (2)$$

where:

g = Acceleration due to gravity (m/s^2).
H = Height between the highest and lowest openings on each wall (m).
$\bar{T}$ = Mean of indoor and outdoor temperature (K).

Wind and stack acting together

Combination by quadrature yields the following expression for the ventilation flow rate, Q(m^3/s), for wind and stack acting together:

$$Q = (Q_W^2 + Q_S^2)^{1/2} \quad (3)$$

Typical mid-range values for the variables in Equations 1 and 2 are as follows:

U — 4 m/s; $\triangle C_p$ — 0.5; g — 9.8 m/s^2; H — 7 m; $\bar{T}$ — 290 K.

Whence, on substitution:

$$Q = 0.6\,A(1 + 0.026\,\triangle T)^{1/2} \quad (4)$$

Single-sided ventilation

Wind

The ventilation flow rate, Q_W(m^3/s), is given by Warren[10] as the following simple expression:

$$Q_W = 0.05\,A.U. \quad (5)$$

where A and U were defined previously for Equation 1.

Stack

The ventilation flow rate, Q_S(m^3/s), resulting from a temperature difference, $\triangle$T (°C), is given by

$$Q_S = C_D.A.(g.h.\triangle T/\bar{T})^{1/2}/3 \quad (6)$$

where

h = Vertical dimension of window opening (m).
C_D, A, $\bar{T}$ were defined previously.

Wind and stack acting together

Combination by quadrature yields the following expression for the ventilation flow rate, Q(m^3/s), for wind and stack acting together:

$$Q = (Q_W^2 + Q_S^2)^{1/2} \quad (7)$$

Typical mid-range values for the variables in Equations 5 and 6 are as follows:

U — 4 m/s; g — 9.8 m/s^2; h — 0.7 m; $\bar{T}$ — 290 K.

Whence, on substitution:

$$Q = 0.2\,A\,(1 + 0.025\,\triangle T)^{1/2} \quad (8)$$

The expressions given in Equations 4 and 8 are, fortuitously but conveniently, similar, and it is suggested that they be replaced by the single expression for ventilation flow rate as function or area of opening, A, and temperature difference, $\triangle$T, which follows:

$$Q = K.A.\,(1 + 0.025\,\triangle T)^{1/2} \quad (9)$$

where K = 0.2 for single-sided ventilation and K = 0.6 for cross-ventilation.

Ventilation rate as a function of outdoor air temperature

The simple regression equation for P, the number of large windows opened wide as a percentage of all windows in occupied rooms, against external air temperature, T_o (°C), is given from Table 3 as follows:

$$P = (1.7\,T_o - 5.6) \quad (10)$$

Examination of the total available area of window opening, per unit floor area of office space, for the five buildings under consideration yields a range from 0.04 to 0.20, with a mean value of 0.13. For present purposes, a value of 0.10 will be used.

Combining the value of this ratio with Equations 9 and 10 the following expression is obtained for the ventilation flow rate, per unit floor area of office space, q (l/s m^2):

$$q = (0.1).(1.7\,T_o - 5.6).K.(1 + 0.025\,(T_i - T_o)^{1/2}).1000/100$$

or

$$q = K.(1.7\,T_o - 5.6).(1 + 0.025\,(T_i - T_o)^{1/2}) \quad (11)$$

Assuming an internal average air temperature of 20°C, values of q have been calculated for a range of values of T_o for the two extreme cases, K = 0.2 and K = 0.6. These are shown in Fig. 6.