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HOW EFFECTIVE IS NATURAL VENTILATION? - A STUDY OF LOCAL MEAN AGE OF AIR BY MODELLING AND MEASUREMENT

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SUMMARY

A condition often assumed when designing a naturally ventilated building is where air enters at low level and leaves at high level due to the stack effect. It then follows that, at upper levels, the air may be relatively 'stale' since it has previously passed through the lower storeys. An analogous situation may arise when wind is blowing, in which the air entering through the windward face becomes stale as it passes through the building to the downwind sections.

It is not well understood how ventilation may, in reality, be affected by this. To address these issues, this report describes a modelling approach using BREEZE and complementary measuremnents using the Passive Tracer Gas technique to study local ventilation rates in multiroomed office buildings. Calculations show that simple ventilation flow rates, as conventionally calculated at the design stage, cannot be relied upon to indicate the true 'freshness'. Measurements show that effective ventilation can be less than current minimum occupancy requirements.

INTRODUCTION

This report describes work carried out as part of a broader study to investigate ventilation efficiency and indoor air quality strategies to minimise energy liabilities in naturally ventilated office buildings. The study was funded by the UK Department of Environment's Energy Related Environmental Issues research programme.

In the design of a naturally ventilated building with many stories, a condition often assumed is where air enters at low level and leaves at high level due to the stack effect. It then follows that, at upper levels, the air may be relatively 'stale' since it has previously passed through the lower storeys. An analogous condition occurs where wind is blowing, and the air entering through the windward face becomes stale as it passes through the building to the downwind sections. Internal partitions (eg closed doors) may also affect the true adequacy of the supply of outside air. At present, it is not well understood how the effectiveness of ventilation may be affected by these factors, and how improved design may avoid the possible problems. To address these issues, BRE has been investigating[1,2,3] the possible application of the concept of 'ventilation efficiency' [4] to naturally ventilated buildings.

The objectives of the current work were to apply the concept of ventilation efficiency to examples of typical, multi-story naturally ventilated office buildings and to:

- assess the distribution of 'fresh' (outside) air supply'
- assess the adequacy of ventilation for the intended occupancy, and
- explore the possible implications for the design and operation of buildings and strategies to ensure adequate air quality, whilst avoiding excessive ventilation.

Two complementary approaches were followed. Computer software for modelling airflow and contaminant movement (BREEZE)[5] was used to calculate local ventilation rates in a multiroomed complex naturally ventilated office building during design and construction.

Complementary to this, the Passive Tracer Gas Technique developed at BRE was applied to measure local ventilation rates in two multistorey office buildings while in use.

MODEL STUDY

The building used for the model study had recently been constructed and ventilation modelling had previously been carried out to provide input to decisions during the design and construction. It incorporated the following key architectural features typical of many recent designs for natural ventilation in the UK:

- a central atrium or covered street, as a means of providing ventilation to adjacent offices either side via windows,
- deep offices with ventilation openings to outside on only one face, with the other face opening to an internal street or atrium, and
- multistorey, with significant vertical ventilation routes.

It consists of an east and west wing linked in a line to a central section. A covered 'street' forms an atrium between the north and south buildings in each section. There are five storeys along the north side of the street and four storeys along the south side. The offices are mainly open plan throughout, except on the fourth and fifth floors where some cellular offices have been considered as options at the design stage. Although the whole building was modelled, this study focuses on the west wing for the purposes of simplicity and clarity. A perspective view (model),of the whole building, and schematic floor plan and cross-section of the west wing are shown in Figure 1. Ventilation is provided by windows to outside and to the 'internal' covered street. Trickle ventilators are installed in each external window to provide controllable background ventilation during cooler months, when windows are expected to be closed.

Approach

The model study approach was based on a protocol previously developed[2] (summarised below) for measuring local mean ages of air using the Passive Tracer Gas Technique. In this, constantly emitting tracer gas sources are distributed evenly throughout a building to give a uniform distribution of tracer emission rate per unit volume. The local mean age is then determined from measurements of the local concentration of tracer gas and its known emission rate.

For the model study, the multi-cell ventilation and contaminant prediction model BREEZE was used to predict the bulk air exchanges between the various ventilated spaces in the building. A uniform 'tracer' emission rate was simulated using the contaminant prediction facility and steady-state tracer gas concentrations (C) were calculated in selected rooms. The local mean age τ_j of the air in room 'j' was calculated as follows:

$$\tau_j = C_j / (S / V) \qquad (1)$$

where S is the source emission rate and V is the room volume.

It is convenient to define a local ventilation rate[2], analogous to the conventional air change rate, as follows:

$$r_j = 1 / \tau_j \qquad (2)$$

We have previously proposed a quantity called the equivalent mean ventilation flow rate[2], defined as equal to the equivalent flow rate of fresh air which would maintain the observed concentration of tracer. This is obtained by multiplying the local ventilation rate by the volume of the space to which it applies. It is convenient to express this as a normalised flow rate per unit floor area, Q_{eq}, eg. in units of litres per second per square metre ($l\ s^{-1}\ m^{-2}$). If the local ventilation rate is expressed in h^{-1}, and the room floor to ceiling height H is in metres, then the normalised equivalent flow rate is given by the following expression:

$$Q_{eq(j)} = r_j \, x \, H \, / \, 3.6 \qquad (3)$$

Test cases

The study focused on how local ventilation rates might vary throughout the building and whether they would meet the minimum requirements in conditions when windows are closed. Three basic cases were considered as follows:

(i) buoyancy dominated - no wind, with the air temperature outside (T_o) lower than inside'

(ii) buoyancy and wind combined - prevailing wind, with air temperature outside (T_o) lower than inside, and

(iii) wind dominated - prevailing wind, but with equal air temperatures inside and outside.

In each of the above cases both average and extreme weather conditions for the south of England[6] were modelled, although only the case with average conditions are reported here. The internal air temperature was taken to be either 18°C or 21°C.

The possible effect on local ventilation rates due to closing the internal doors to the cellular offices was also considered. A small gap of 0.041 m^2 was assumed around each closed door, and the calculations carried out for average conditions in the combined wind and buoyancy case as above.

Results

The results were compared with recommended and minimum ventilation rates[7] expressed per person and per unit floor area for occupancies of 10 m^2 and 14 m^2, taken to represent minimum and recommended values[8], as shown in Table 1.

Table 2 shows the result for the three cases. Figure 2 shows the local ventilation rates at increasing storey height above ground. Where wind is blowing, zone numbers corresponding to the left of Figure 1b have at least one wall generally facing windwardand.

For the buoyancy dominated case, it can be seen from Table 2 that the total flow rates meet or exceed the minimum recommended rate (0.35 $l\ s^{-1}\ m^{-2}$) on all but the third level. Ventilation is at a minimum on the third level, which is approximately at the neutral plane. Below this level, air enters the offices from outside. Above it, air enters from the internal street and leaves through the external facade.

As expected, the equivalent ventilation rates are highest and similar to the total rates on the lower storeys, where air enters from outside. Equivalent rates are small near the neutral level (at mid-height) where air exchanges are at a minimum. On the two levels above the neutral plane, equivalent ventilation rates are approximately one-third of the total rates and are less than the minimum requirement. This is because the supply air is generally from within the building.

In the combined case of buoyancy and wind, the total flows achieve the minimum throughout the building. The equivalent flows, however, reveal a more complicated picture. Rooms with at least one windward wall generally have equivalent ventilation rates which meet the minimum requirement. Effective ventilation is not achieved in a significant number of rooms at all levels. There were no significant changes in these results when calculations were repeated with doors closed (but for a small gap).

The situation deteriorates further in the wind dominated case. Although total ventilation rates appear to be adequate, equivalent rates show that ventilation is below requirements on the lower three storeys and in the cellular office on the top storey.

FIELD MEASUREMENTS IN TWO OFFICE BUILDINGS

To complement the model study, measurements were carried out in two naturally ventilated office buildings as described below, using a protocol for the application of the Passive Tracer Gas Technique developed at BRE[2,3]. The measurements are described only in brief here to present the key results; more details will be published separately[9].

The general principle is the same as used for the model simulations. Passive tracer gas permeation sources are placed in rooms and corridors throughout the building to achieve a source emission rate which is broadly in proportion to floor area (within about 10%). Diffusion-type air samplers are subsequently placed in a selection of typical rooms, and the average concentration (C) is determined from the mass collected over the measurement period (days or weeks) and the known diffusive sampling rate. The local mean age, τ_j, within a room of volume V is then calculated using equation (1).

Procedure

Tests were carried out in winter to measure the average ventilation rates at different locations in the buildings over a range of weather conditions. Samplers were placed in triplicate (to check accuracy) at 25 locations in Building A and 24 in Building B. These were collected for analysis after four weeks in Building A and after three weeks in Building B. A limited set of preliminary measurements were also carried out over 48 hours in Building A at five locations.

Building A

Building A was a fairly typical 1960's narrow plan, four storey office block in a suburban location north of London (Figure 3). A building of similar height stood immediately to the north, whilst to the east the ground was built-up and steadily rising and open to the west and south. The building was primarily naturally ventilated, but with mechanical extract in some photographic studio rooms on the third floor. The openable windows were mainly side hung casements, but with some louvred units in stairwells and toilets. Offices were mainly cellular (around 13 m^2), but with some open plan rooms (approximately 40 to 90 m^2).

Building B
Building B was a four storey office block, built in the mid eighties in an urban location in the midlands. Built over an existing single storey office block, it was basically rectangular in plan (Figure 4) with each storey overhanging the lower. It is unusual in that it was naturally ventilated from the perimeter but deep in plan, with no central atrium for additional ventilation. To the north and west were a pair of two-storey buildings whilst the other directions were unobstructed.

Offices were arranged around a central core (for services and fire escape) and an open stairwell surrounded by open circulation or meeting areas. An almost isolated mezzanine floor was sandwiched between part of the ground and second floors. The ground floor consisted of an open plan office and a large, tall reception area. The first floor was open plan. The second floor was mainly open plan but with some cellular offices. The third floor consisted of mainly single or double occupancy offices, some of which were air-conditioned, with a few large rooms for occasional use. Window bays consisted of an inwardly opening top 'hopper' pane above a light shelf and a lower 'tilt or turn' section.

Results

Building A

As before, the results are compared with the recommended ventilation supply rates (Table 1). For Building A, Table 3 shows the measured local ventilation rates, normalised equivalent ventilation supply rates and nominal floor areas for each room for both the preliminary and long term tests. The average meteorological data are also given for the same period. It may be seen that long term averaged local ventilation rates were spread over an order of magnitude, ie 0.3 to 3.6 per hour. The standard error of measurement is better than 15% except where indicated.

The variation in rates appeared to be dominated by window opening behaviour. It was not expected that room size should be a significant factor, since most rooms differed only in their length, along which openable windows were generally regularly spaced. Results for the large cross-ventilated rooms 012, 222b and 229 were not exceptional.

Corresponding to the above, equivalent supply rates were in the range 0.25 to 2.8 $l\ s^{-1}\ m^{-2}$ and mostly just above the minimum requirement (Table 1). Exceptions were some small rooms on the south face of the second floor with double occupancy. The low ventilation rate of 0.25 $l\ s^{-1}\ m^{-2}$ in the large room 229 was adequate for the low occupancy (two persons) noted.

Room 001 showed a relatively high ventilation rate. This was used by several office messengers and was fitted with a number of window slats which were usually open. On the third floor, where ventilation rates were generally high, occupants were noted to frequently open windows, perhaps to dilute odours from film processing activities carried out on that floor.

Ventilation rates in the 48-hour tests were broadly half to two-thirds of the long term values. This may be consistent with limited CO2 measurements which showed peaks exceeding 1400 ppm over short periods. This level corresponds to a ventilation rate of 5 $l\ s^{-1}$ per person for an average person in office type activity[10].

Building B

Results for Building B are shown in Table 4. Time-average local ventilation rates were in the range 0.26 to 0.78 per hour and equivalent air supply rates in the range 0.22 to 0.64 $l\ s^{-1}\ m^{-2}$. Ventilation rates were generally lower on the second floor. It is not clear whether this could be related to a possible neutral level for stack-driven ventilation, as no supplementary measurements were carried out to investigate this.

The observed floor area per workstation was approximately 10 m^2 on the ground and second floors respectively. The minimum recommended ventilation rate of 0.5 $l\ s^{-1}\ m^{-2}$ was met on the ground floor but not on the second. First floor occupancy was approximately 18 m^2 per person, for which the minimum recommended ventilation rate of 0.28 $l\ s^{-1}\ m^{-2}$ was exceeded. On the third floor, which mainly contained single and double occupancy rooms and a large 'boardroom', the minimum recommended ventilation rate per person was either met or exceeded.

CO2 concentrations recorded near location 2.1 frequently exceeded 1400 ppm (corresponding approximately to 5 $l\ s^{-1}$ per person). This is consistent with the measured ventilation rates which were between one-half to four-fifths of the recommended minimum for the given occupancy.

CONCLUSIONS

The objectives of this study were to apply the concept of ventilation efficiency to assess the effectiveness of natural ventilation in typical examples of multi-storey office buildings, and to explore the possible implications for the design, operation and ventilation strategies in buildings. Both a computer modelling and experimental approach were followed. The local mean age of air was determined which was used to calculate an equivalent ventilation rate of 'fresh air' in $l\ s^{-1}\ m^{-2}$.

The model study was carried out for average meteorological conditions in three cases, (i) buoyancy dominated, (ii) combined wind and buoyancy driven and, (iii) wind dominated. In all cases it was predicted that ventilation, as expressed by equivalent ventilation rates, may be expected to be less than currently recommended minimum ventilation supply rates for occupants in a significant number of rooms. In general, however, the simple ventilation air flow rates were greater than the equivalent flow rates and, consequently, were not an accurate guide to the true adequacy of ventilation for diluting internally generated contaminants.

Local ventilation rates were measured in two multi-storey office buildings in winter using a protocol for measuring local mean ages developed for the Passive Tracer Gas Technique. The time-averaged equivalent ventilation rates were shown to vary by over an order of magnitude throughout one building, but mostly just above the minimum requirements for the occupancy. Equivalent ventilation rates in the second building varied by over a factor of three and achieved the minimum requirements on all but the second storey.

Taken together, these results suggest that the concept of ventilation efficiency, applied in the form of the local ventilation rate and equivalent ventilation rate, provides a valuable measure of the ventilation performance throughout naturally ventilated buildings. Both measured and predicted equivalent ventilation rates showed that ventilation can be less than current minimum occupancy requirements. Simple ventilation flow rates, as conventionally calculated at the design stage, cannot be relied upon to indicate the true 'freshness' or capability of the ventilation supply for diluting internally produced contaminants.

Further full scale measured data are necessary to establish a representative view of the ventilation performance of the UK office building stock, together with model studies to understand the impications for design in more general terms. However, the following preliminary recommendations are suggested to help avoid problems identified above:

(i) The optimum arrangement of inlets and outlets (ventilation strategy) for background ventilation should be sought.

(ii) The design should consider the meteorological conditions likely to occur for significant numbers of days (the case when there is no wind cannot be generalised as the worst case fo the UK).

(iii) To ensure effective control, specialist attention should be given to ensure background leakage is small compared to purpose provided ventilation.

(iv) An effective control strategy should be evaluated for opening small vents or fine control of small window openings.

(v) It may be necessary to consider special inlets and outlets (eg ducted outlets via towers etc.) to ensure that air flows in the required direction within the building.

(vi) Consider sensors (eg CO_2) to control openings automatically according to occupancy requirements if necessary.

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(l s^{-1})	Per person	Per m^2 floor area (10 m^2)	(14 m^2)
Recommended:	8	0.8	0.57
Minimum:	5	0.5	0.35

Table 1. Required ventilation rates (l s^{-1}) per person and per unit floor area with either 10 m^2 or 14 m^2 per occupant.

Location:	1.2	1.4	2.2	2.4	3.2	3.4	4.2	4.3	4.5	4.6	5.2	5.3
Area (m^2)	910	839	900	830	900	830	150	750	680	150	750	150
	(i) Buoyancy Only											
r (h^{-1})	0.77	0.72	0.56	0.54	0.11	0.11	0.19	0.22	0.22	0.19	0.22	0.17
Q_{eq} (ls^{-1}m^{2})	1.01	0.94	0.66	0.63	0.12	0.12	0.22	0.26	0.26	0.22	0.25	0.20
Q_{in} (ls^{-1}m^{2})	0.95	0.88	0.59	0.60	0.06	0.06	1.60	0.76	0.74	1.72	1.03	0.53
acr (h^{-1})	0.73	0.68	0.51	0.51	0.05	0.05	1.37	0.65	0.64	1.47	0.88	0.45
	(ii) Combined Buoyancy & Wind											
r (h^{-1})	0.18	0.50	0.16	0.41	0.14	0.22	0.86	0.33	0.45	1.25	0.24	0.17
Q_{eq} (ls^{-1}m^{2})	0.24	0.65	0.19	0.48	0.17	0.25	1.00	0.38	0.52	1.46	0.28	0.20
Q_{in} (ls^{-1}m^{2})	0.42	0.61	0.80	0.45	0.96	0.51	1.17	0.38	0.88	1.29	0.62	0.36
acr (h^{-1})	0.32	0.47	0.68	0.38	0.82	0.44	1.00	0.32	0.75	1.11	0.53	0.30
	(iii) Wind Only											
r (h^{-1})	0.15	0.21	0.17	0.22	0.19	0.24	1.18	0.41	0.67	1.86	0.60	0.24
Q_{eq} (ls^{-1}m^{2})	0.19	0.27	0.20	0.25	0.23	0.28	1.38	0.47	0.78	2.17	0.70	0.28
Q_{in} (ls^{-1}m^{2})	1.06	0.53	1.00	0.54	1.01	0.54	1.36	0.45	0.93	2.13	0.76	0.34
acr (h^{-1})	0.82	0.41	0.86	0.46	0.87	0.46	1.16	0.38	0.80	1.83	0.65	0.29

Note: Q_{in} = total inflow divided by zone area; acr = air change rate (total inflow / zone volume)

Table 2: Equivalent and total ventilation rates calculated from model study

Location:	323	319	311	309a	309	307	303	229	225	224	222b	219	218	214	210	206	204	202
Area (m^2)	13	13	10	11	10	29	11	81	21	62	91	40	13	13	13	13	30	16
Q_{eq} ($ls^{-1}m^{-2}$)	0.35	0.46	1.4	1.3	2.8	0.52	0.93	0.36	0.28	0.41	0.51	0.53	0.60	0.46	0.43	0.42	0.48	0.50
r (h^{-1})	0.43	0.59	1.8	1.7	3.6	0.66	1.2	0.46	0.36	0.53	0.66	0.69	0.77	0.59	0.55	0.54	0.62	0.64
Location:	022	016	012b	012	001	0S	0N	48 hr tests:				307	229	222b	206	012		
Area (m^2)	45	13	13	129	16	31	16	(0N = corridor north)				28.6	80.7	91	13	129		
Q_{eq} ($ls^{-1}m^{-2}$)	0.25	0.44	0.30	0.33	1.8	2.0	1.1	(0S = corridor south)				0.23	0.21	0.20	0.21	0.17		
r (h^{-1})	0.32	0.57	0.38	0.41	2.3	2.6	1.4					0.30	0.27	0.26	0.27	0.22		

Notes: room prefix denotes storey; ceiling height 2.8 m; average test conditions as follows:-

(i) 4 wk test: T_i = 17.9 °C, T_o = 6.7 °C, ws = 4.2 ms^{-1}, wd = 210°

(ii) 48 hr test: T_i = 19.3 °C, T_o = 4.7 °C, ws = 4.4 ms^{-1}, wd = 210°; where

Q_{eq} = equivalent flow rate, normalised by floor area; r = 1/τ; τ = local mean age;

T_i, T_o = air temperature (i) inside, (o) outside; ws/wd = wind speed/direction (clockwise from N)

Table 3. **Winter - Building A ; measurements over 4 week period (2.2.95 to 2.3.95) and 48 hr period (25.1.95 to 27.1.95)**

Location:	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	3.10	2.1	2.2	2.3	2.4	2.5
Area (m^2)	49	21	-	39	31	43	40	40	38	124	(---312---)		42	25	95
Q_{eq} ($ls^{-1}m^{-2}$)	0.32	0.34	'lost'	0.24	0.41	0.46	0.54	0.47	0.57	0.37	0.22	0.27	0.38	0.27	0.27
r (h^{-1})	0.39	0.41	'lost'	0.3	0.5	0.55	0.65	0.57	0.69	0.45	0.26	0.32	0.46	0.33	0.33
Location:	1.1	1.2	1.3	1.4	1.5	1.6	1.7		0.1	0.2					
Area (m^2)	(----------------- 444-----------------)						26		(---134---)		(-- --) denotes common				
Q_{eq} ($ls^{-1}m^{-2}$)	0.48	0.64	0.50	0.46	0.47	0.34	0.51		0.54	0.58	open plan area				
r (h^{-1})	0.57	0.78	0.61	0.55	0.57	0.41	0.62		0.66	0.71					

Notes: room prefix denotes storey; ceiling height 3.0 m; average test conditions as follows:-

T_i = 23.0 °C, T_o = 5.6 °C, ws = 4.5 ms^{-1}, wd = 240°; where

Q_{eq} = equivalent flow rate, normalised by floor area; r = 1/τ; τ = local mean age;

T_i, T_o = air temperature (i) inside, (o) outside; ws/wd = wind speed/direction (clockwise from N)

Table 4. **Winter - Building B; measurements over 3 week period (7.3.95 to 28.3.95)**

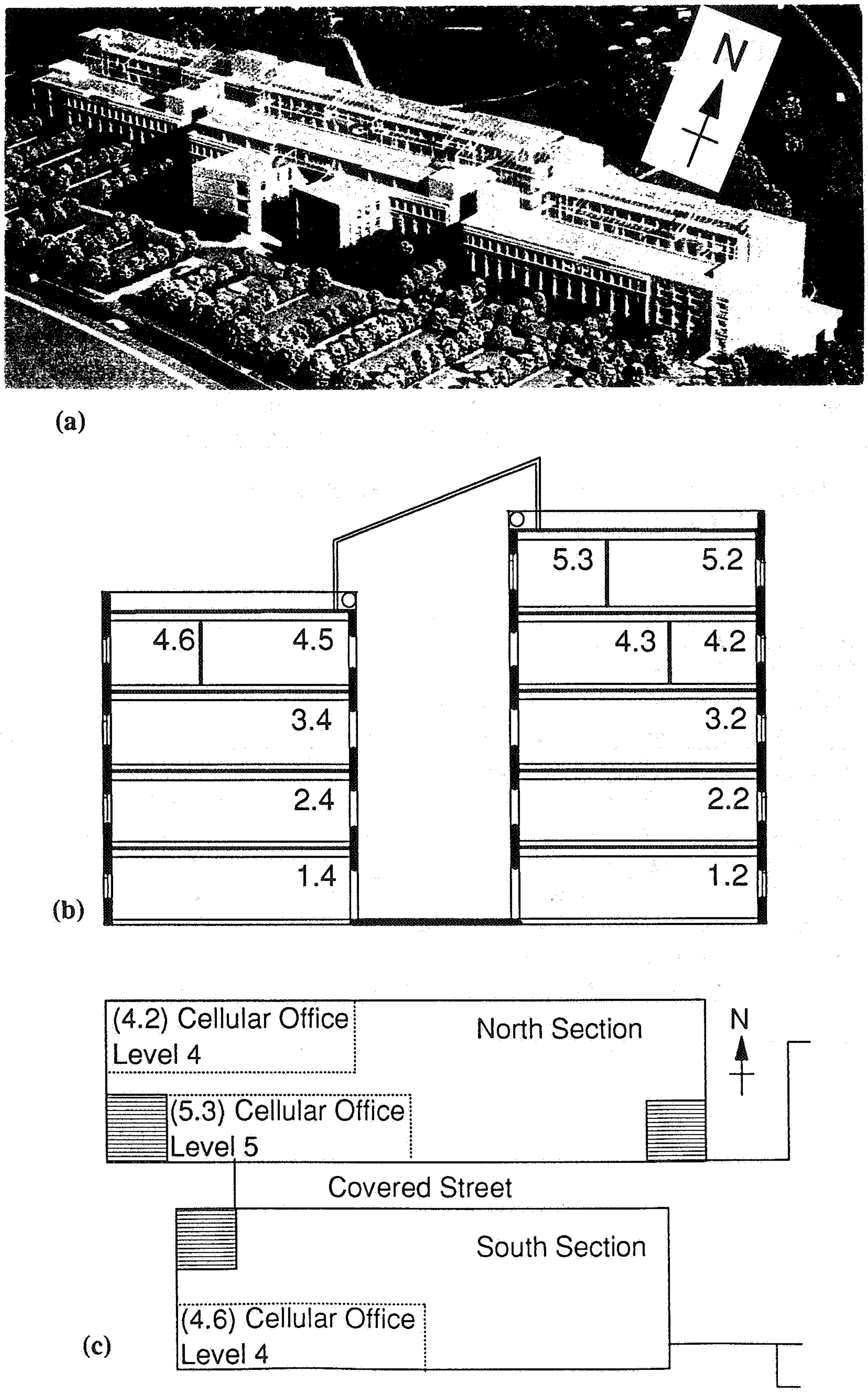

Figure 1. (a) Perspective view (model) of whole building, (b) cross section showing zone numbers, and (c) floor plan, of west wing.

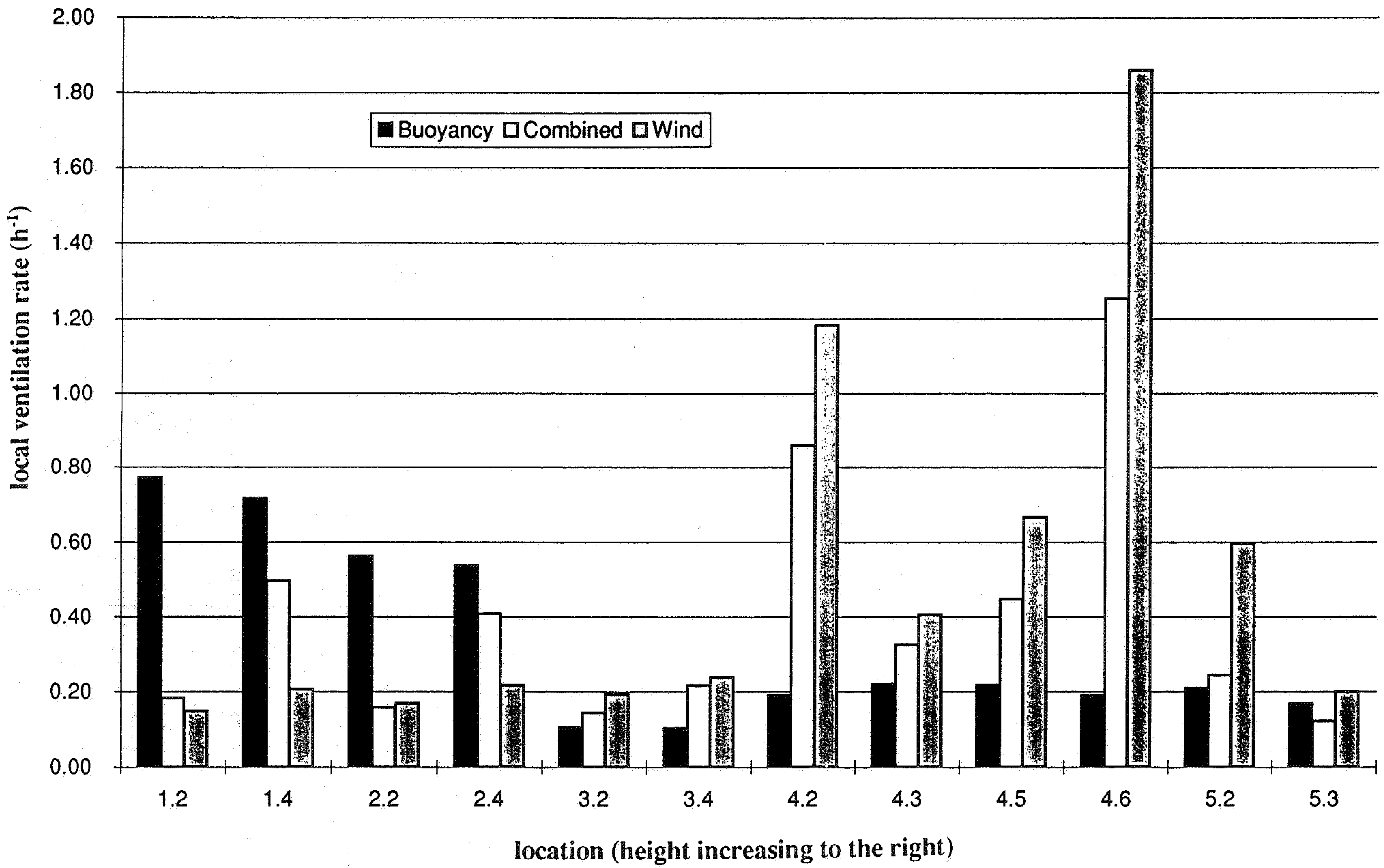

Figure 2. Local air change rate for each zone, shown with height increasing to the right.

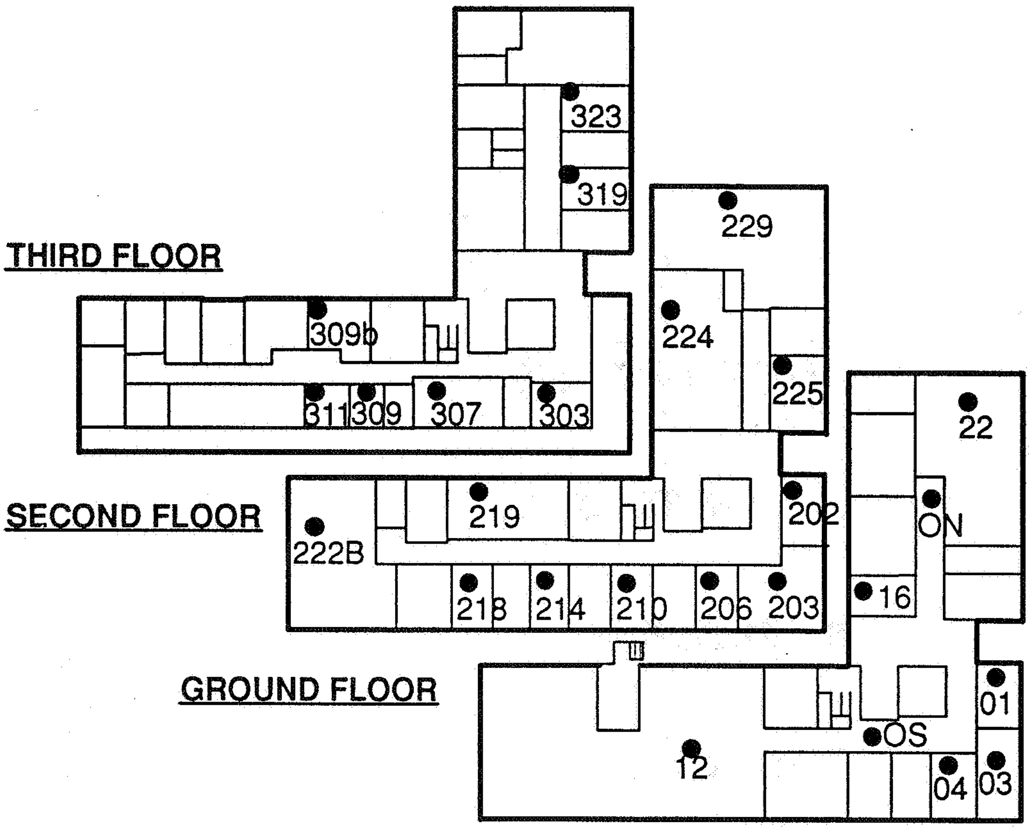

Figure 3. Building A; floor plans and measurement zones.

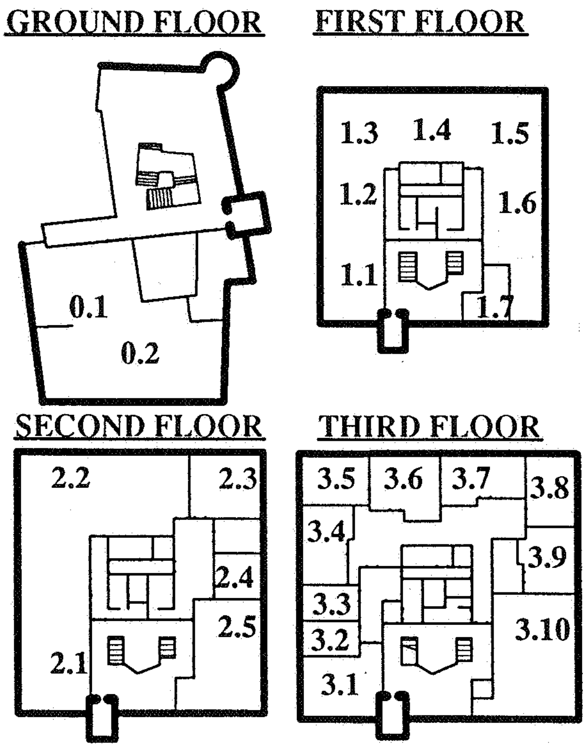

Figure 4. Building B; floor plans and measurement zones.