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Summary This paper describes field measurements to assess the effectiveness of trickle ventilators in providing adequate and controlled background ventilation in office buildings during the heating season. The tests were at full-scale in two multi-storey office buildings. Both are located within a built-up area and recently refurbished. Carbon dioxide, air ventilation rates, temperatures and relative humidity were monitored for two weeks in one open-plan office in both buildings. It was concluded that resultant internal airspeeds are low, thus minimising the possibility of cold draughts. Metabolic carbon dioxide levels are not excessive and adequate ventilation is provided. It was also found that occupants use trickle ventilators regularly to control their environment once they are familiar with their operation.

Trickle ventilators: Field measurements in refurbished offices

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1 Introduction

Approved Document Part F1 (Ventilation) of the *UK Building Regulations*[1] came into force in 1995. The Document advises that new naturally ventilated office buildings should have provision for purpose-designed background ventilation. Guidance states that this can be provided via external openings, with at least 400 mm^2 total openable area per square metre of floor area. Correctly sized trickle ventilators are a common means of providing this background ventilation. They can contribute to the overall concept of 'build tight — ventilate right'[2] which aims to provide controlled background ventilation using suitable openings in an airtight building envelope. Trickle ventilators can also be used as part of a natural ventilation strategy in buildings where this can provide for winter background ventilation[3].

This paper first briefly describes computer modelling and laboratory tests carried out at the Building Research Establishment to assess the effectiveness of trickle ventilators in providing adequate and controlled background ventilation in office buildings during the heating season. The paper then details the results from field measurements carried out in two offices recently refurbished and equipped with trickle ventilators.

2 Previous work

In 1992 a study[4] using a multi-zone air flow prediction computer program BREEZE[5] was carried out to assess whether including permanent and controllable background trickle ventilators could provide adequate background ventilation in commercial buildings. The study recommended that adequate ventilation could be provided with 4000 mm^2 open-area ventilators used in rooms with floor areas less than 10 m^2 and with 400 mm^2 per m^2 (of floor area) for larger rooms.

This was confirmed by a full-scale laboratory study[6] in the heating season of 1993/94. The study took place in two deep-plan office rooms with a depth of 7.5 m and an area of approximately 26 m^2. One room was used as a control and the other was fitted with a trickle ventilator (with opening area of 10 500 mm^2, corresponding to 400 mm^2 per m^2 of floor area) fixed to its main south-facing window. Varying levels of occupancy were simulated in both rooms by constant CO_2 injection (to simulate metabolic rate) and heat sources (lamps). Internal measurements included monitoring CO_2 levels, air velocity and temperature as well as ventilation rate using SF6 tracer gas decay. External measurements included wind velocity, wind direction and temperature.

Figure 1 presents the results from one of the experiments for a typical working day. This shows that CO_2 levels in the room with the trickle ventilator are on average 700 ppm lower than in the control room without ventilators. The same figure shows that wind was mostly from south to north-west, that the outside wind speed was between 3 and 7 m s^{-1} and that the inside/outside air temperature difference was about 15–16°C; higher values are observed in the control room, indicating warmer internal conditions. The air change rate in the room with the trickle ventilator was higher at about 1.2 ac h^{-1}, compared with 0.6 ac h^{-1} in the control room.

Figure 2 demonstrates the effect that outside wind speed has on the CO_2 levels in the room with the ventilators. Although CO_2 levels are lower with higher outside speed, the CO_2 values were well below the level of 1000 ppm usually taken to indicate an adequate supply of fresh air of about 5 l s^{-1} per person.

To further confirm these findings in the field, measurements were made in two occupied office rooms equipped with trickle ventilators during the winter of 1994/95[7]. Measurements included air velocity at desk and ankle heights at distances of 1 m and 2 m away from the window fitted with trickle ventilators. All draught measurements within the rooms were significantly lower than the 0.3 m s^{-1} threshold[8] considered as the upper limit above which discomfort is likely to be felt through draughts during the winter. Further confirmation was that occupants did not complain about cold draughts.

The CO_2 levels recorded in both occupied offices have reconfirmed the findings of the laboratory study. This had shown that CO_2 concentration did not exceed 1000 ppm when the ventilator was sized correctly for the office occupancy. Although the tests were not extensive, the following general conclusions were drawn:

— Trickle ventilators with a minimum openable area of 400 mm^2 per m^2 (of office floor area) can provide adequate background fresh air during winter and maintain good indoor air quality (IAQ) (using CO_2 as the surrogate indicator) within a typical office room located in a suburban site.

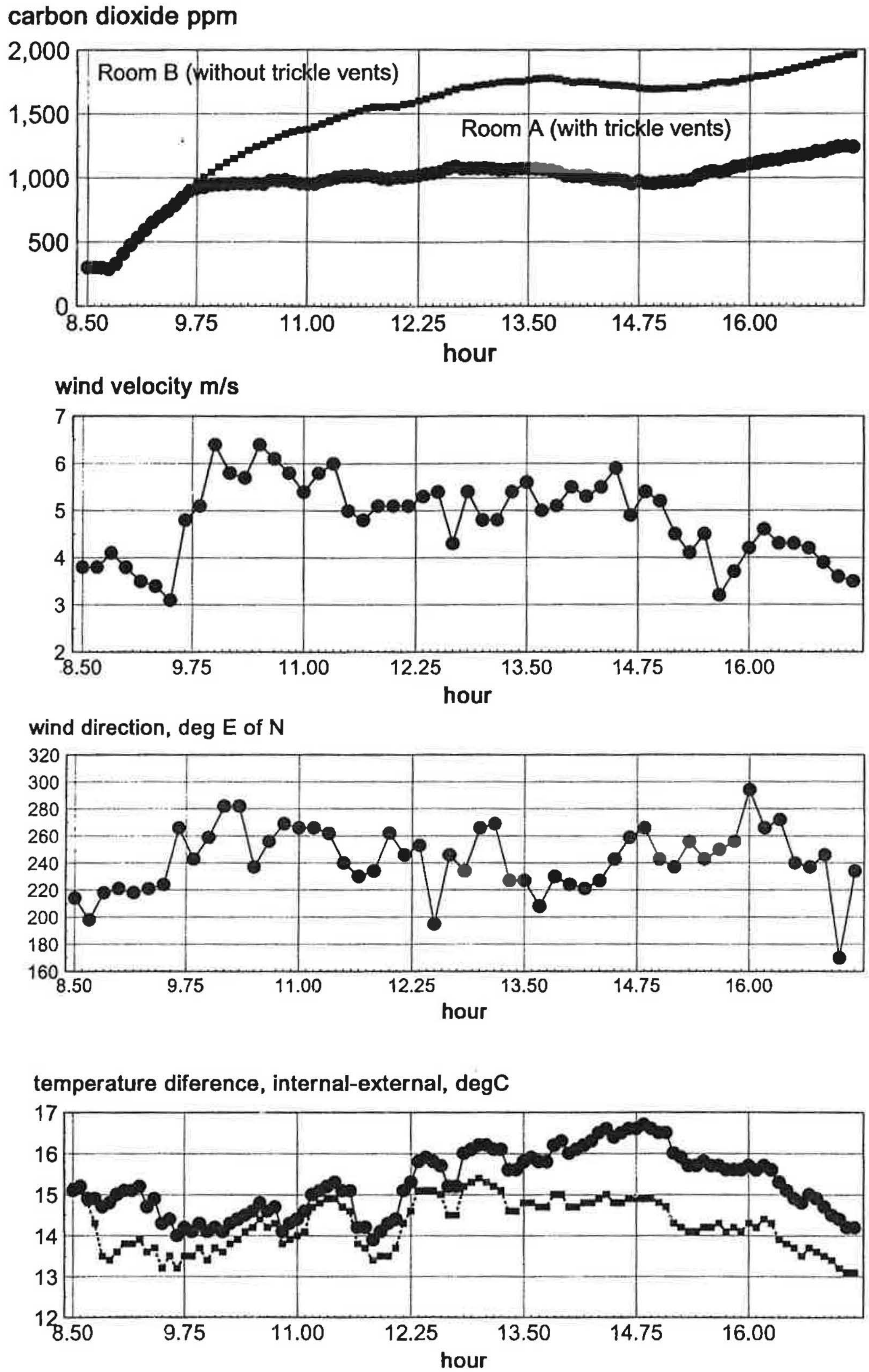

Figure 1 Plot of typical experimental results: Carbon dioxide concentration during a working day in two adjacent experimental rooms occupied by three people, under typical external conditions.

— Transient increased occupancy increases the internal metabolic CO_2 level, but this can be restored to normal levels relatively rapidly when normal occupancy is resumed.

— Well designed ventilators, correctly positioned, should not produce cold draughts.

— Internal temperatures can be maintained with open ventilators even though the external temperatures may be low.

— Long-term CO_2 monitoring could be used as a marker of indoor air quality.

3 Field measurements

Full-scale tests were carried out in two multi-storey office blocks in the heating season of 1995. Both blocks are in built-up urban areas, four storeys high, and used mainly for clerical

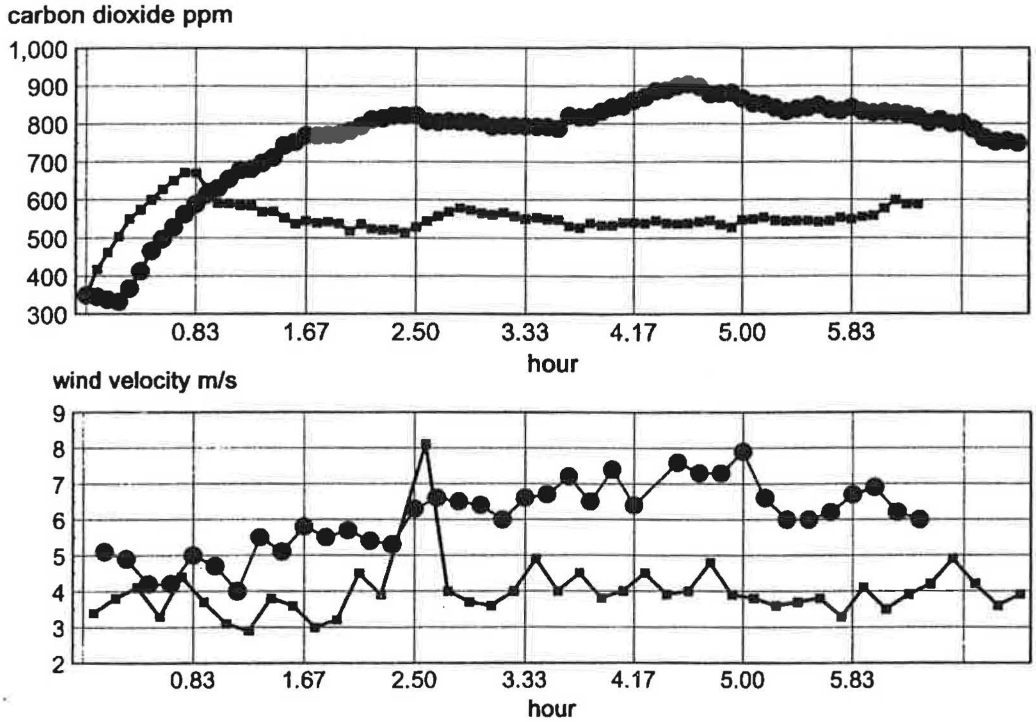

Figure 2 Effect of external wind velocity on the performance of trickle ventilators (with constant wind direction and constant inside/outside air temperature difference)

and administrative work. The buildings had recently been refurbished, including trickle ventilators which could be manually opened or shut by the occupants.

A room in each building was monitored continuously for two weeks during the heating season. Appropriately located equipment was undisturbed during data logging. After the first monitoring period the equipment was removed from the first building and set up in the second building where it was left for a similar period.

The room selected in each building was a large open-plan office occupied by several people. The trickle ventilators were fully open at the beginning of the first week and fully closed at the beginning of the second, in both offices. However, the occupants were free to alter the arrangement at their own discretion. They did use the ventilators. Therefore only initial and final ventilator conditions are known. At no time were all the ventilators either fully open or fully closed during a whole week.

3.1 Building 1 (B1)

The monitored space was located on the first floor of the building. It was a large open-plan office of about 250 m² floor area, occupied by about fifteen people. Figure 3 is a schematic plan of the space with the monitoring position marked. The office was occupied only at one end with about 10 m² of floor-space per occupant. The other end was unoccupied. The occupied part of the office was oriented mainly east/west with windows facing south, north and east. The windows could not be opened. Ventilation was provided by a trickle ventilator at the top of the window or by a larger openable panel underneath the window. As it was winter it was expected that the lower panel would not be used. The office was in general use from Monday to Friday and closed over the weekend.

3.2 Building 2 (B2)

The monitored space was on the second floor of the building. It was an open-plan office of floor area about 86 m², occupied intermittently by up to five people. Figure 4 is a schematic plan of the space with the monitoring position marked. The

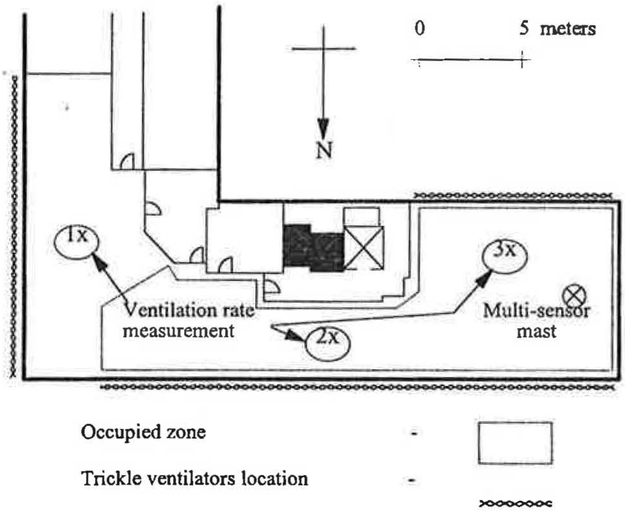

Figure 3 Diagram of office layout — Building 1

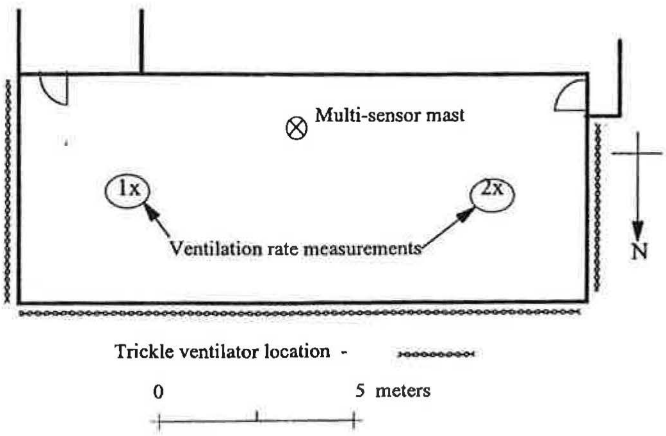

Figure 4 Diagram of office layout — Building 2

office was orientated east/west with the windows facing north. The windows could be opened to provide increased ventilation. During the winter it was expected that only the trickle ventilators would be used. The office was used from Monday to Friday and closed at the weekend. Occupancy was reduced during the latter half of the monitoring period by staff taking annual leave.

3.3 *Environmental monitoring*

A measuring station was set up in the office being monitored. This comprised a mast on which several instruments and appropriate loggers were fixed:

- two ultrasonic anemometers, one at the head height of a seated occupant and the other at ankle height
- a CO_2 sensor fixed at sitting head height
- a temperature sensor
- a humidity sensor.

Ventilation was measured using the perfluorocarbon tracing (PFT).[9] PFT measures the ventilation rate averaged over a selected period. Source tubes emit tracer gas into the air and sampling tubes adsorb tracer from the air. Measurements were made at three locations in B1 and at two locations in B2. The locations of the measuring mast and the PFT air sampling tubes are marked on Figures 3 and 4.

A temperature sensor was placed outside the building to measure external temperature. Weather data (temperature, wind speed and wind direction) were obtained from the nearest meteorological office.

Each occupant in both offices was given a chart on which to record the following:

- occupancy levels
- position of window blinds (up/down)
- position of trickle ventilators (open/closed)
- position of lower ventilators (B1) or windows (B2) (open/closed).

Towards the end of the monitoring period, a questionnaire was administered. This addressed the office environment and the degree of control over it perceived by each occupant.

4 Results and analysis

4.1 *B1*

Similar numbers of trickle ventilators (seven) were found open at the end of each week of monitoring in the occupied part of the space. On the east wall the trickle ventilators were all open during the first week and closed during the second, i.e. they remained as positioned by the researcher. Figure 5 shows the internal conditions and weather data recorded for the second week of monitoring. Table 1 summarises conditions for both weeks.

Returned charts and questionnaire responses showed that during both weeks the trickle ventilators were adjusted. During the first week some occupants closed their trickle ventilators. During the second week the ventilators in the occupied zone were undisturbed at the request of the occupants, whereas the ventilators in the unoccupied zone were closed. The reason given by all those asking for adjustment was to reduce draughts, rather than their feeling cold or because of odours. Only one occupant opened the lower ventilator during the monitoring period. Their usage chart showed that the window was open for a similar period of time and at similar times of day in each week.

Table 1 Results of monitoring in Buildings 1 and 2

		Building no.			
		1		2	
		Week 1	Week 2	Week 1	Week 2
Airspeed at head height (m s^{-1})	Min.	0.0	0.0	0.0	0.0
	Ave.	0.02	0.02	0.05	0.05
	Max.	0.19	0.07	0.14	0.11
Airspeed at ankle height (m s^{-1})	Min.	0.0	0.0	0.0	0.0
	Ave.	0.06	0.06	0.06	0.04
	Max.	0.18	0.2	0.21	0.2
Carbon dioxide concentrarion (ppm)	Min.	259	353	326	316
	Ave.	532	564	605	505
	Max.	1752	1353	1289	1036
Internal temperature (°C)	Min.	17.1	17.5	13.9	14.2
	Ave.	20.5	20.1	20.0	20.0
	Max.	26.9	23.8	24.8	25.2
External temperature (°C)	Min.	4.9	−2.3	−1.8	1.7
	Ave.	9.8	6.9	3.0	3.7
	Max.	14.0	15.0	7.7	5.6
Relative humidity (%)	Min.	19.0	19.2	19 2	18.8
	Ave.	38.4	33.6	25.0	25.0
	Max.	46.5	45.4	33.8	30.5
Wind speed (m s^{-1})	Min.	0.0	0.0	0.0	0.0
	Ave.	3.0	3.0	2.2	3.5
	Max.	9.25	6.7	7.2	8.7
Wind direction (°N)	Ave.	145	69	49	55
Ventilation rate (ac h^{-1}) (PFT method)	Ave.	—	0.96	0.93	0.52

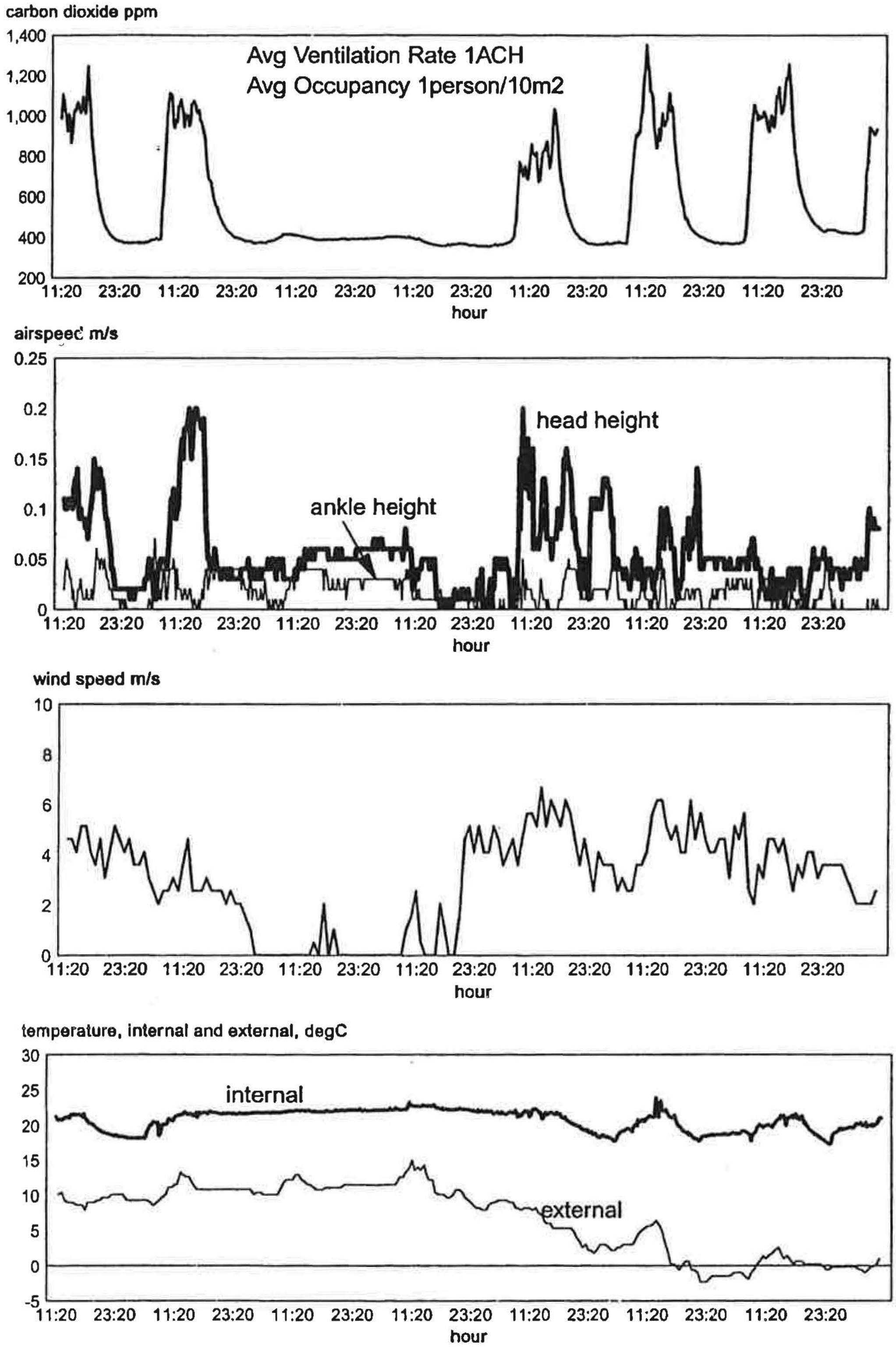

Figure 5 Plot of typical results measured during one week's monitoring in Building 1

During the first week when the ventilators were kept open, the average concentration of metabolic carbon dioxide (CO_2) was about 530 ppm. These levels usually peaked in the early afternoon, reaching a maximum of about 1700 ppm (on one occasion), although a peak of about 900 ppm was more usual. Average airspeeds were low at 0.02 m s^{-1} at head height and 0.06 m s^{-1} at ankle height. At ankle height the airspeeds were generally higher than those at head height; peaks commonly occurred at about 0.1 m s^{-1}. All other parameters were within reasonable limits, although humidity was towards the lower end of the scale at 38 %.

During the second week, the measured average ventilation rate was 0.96 ac h^{-1}, measured at three locations within the room. The average concentration of CO_2 was about 560 ppm, which is consistent with the measured air change rate, and with the average flow rate per person per unit floor area which prevailed during the monitoring period. CO_2 concentration peaked at 1350 ppm on one occasion, and followed patterns typical of an occupied office during the weekdays. Head-height airspeeds averaged 0.02 m s^{-1} and ankle-height airspeeds about 0.06 m s^{-1}. Internal temperatures varied between 17.5 and 24°C and relative humidity between 20 and 45%. Given the very cold weather during the second half of this week, humidity levels are acceptable, although sometimes tending to low levels.

The results for the two weeks of monitoring were similar for all parameters except for relative humidity. This was affected by a drop in external temperature and fell from about 42% to about 20%.

The questionnaire results were difficult to interpret. Their general tendency was that occupants were satisfied with their environment and that they were aware of how to control their conditions.

4.2 B2

A similar number of trickle ventilators were found open at the end of each monitoring week. This indicates that people made use of them. Return rate for the window/vent usage chart was very poor. However, when asked the occupants said that they did adjust the trickle vents during the day. Table 1 shows average values of all measured parameters. During the first week of monitoring average airspeeds were low at 0.05 m s^{-1} at head height and 0.06 m s^{-1} at ankle height. CO_2 showed an average concentration of 600 ppm. The ventilation rate measured at two locations was 0.93 ac h^{-1}. The other measured parameters were within reasonable limits. Air temperature and relative humidity ranged from 14 to 25 °C and from 19 to 34 % respectively.

Figure 6 shows the measured values during the second week. The measured ventilation rate during this period was 0.52 ac h^{-1}, i.e. reduced by half that measured during the first week. This resulted from the closure of most of the trickle ventilators. The weather data showed that while the wind direction was virtually the same for both weeks, the wind speed was higher (by 60%) during the second week. CO_2 levels averaged 500 ppm with peaks of about 1000 ppm. Air temperature and relative humidity ranged over values similar to those of the first week. Airspeeds measured during the second week of monitoring gave average values of 0.05 m s^{-1} at head height and 0.04 m s^{-1} at ankle height.

5 Conclusions

The objective of monitoring the environmental conditions in two multi-storey office buildings was to gain insight into the effectiveness of trickle ventilators in offices. Monitoring took place for two weeks in each office. The decision whether to open or close the trickle ventilators was left with the occupants, who did operate them to give the desired conditions.

In B1, low inside air speeds were recorded during both one-week periods. When most of the trickle ventilators were open, airspeeds at ankle height were generally slightly higher than when most of the trickle ventilators were closed, and also higher than those measured at head height. Airspeeds at head height were similar during both periods. Recorded CO_2 levels reached peaks of about 1000 to 1400 ppm. This is not unreasonably high for this type of building. CO_2 concentrations were similar during the two weeks of monitoring. Ventilation rate was only measured during the second week of monitoring, so no comparison between the two trickle ventilator regimes is possible. However, the CO_2 concentrations were consistent with the ventilation rate and air flow rate that was measured.

In B2, airspeeds recorded during both periods were low. Average airspeeds were similar for ankle and head height. Airspeeds were similar during each one-week period at ankle and head height. CO_2 concentrations recorded during the first week of monitoring were broadly similar to those recorded during the second week; CO_2 levels mostly peaked at about 1200 ppm. While taking the weather into consideration, air change rates measured during both periods show greater ventilation with the trickle ventilators kept open.

It is interesting to compare the profiles of CO_2 during the second week in the two buildings (Figures 5 and 6). Average ventilation rate is 1 ac h^{-1} in B1 and the occupancy is approximately 1 person per 10m² floor area. CO_2 level has peaked to 1400 ppm during the week. In B2 occupancy is much lower at 1 person per 25 m² floor areas and the ventilation rate is 0.5 ac h^{-1}. CO_2 level has peaked to about 1000 ppm in this case. Questionnaire responses indicated that occupants were in control of their environment. They adjusted the ventilator to such a position that environmental conditions were acceptable to them. The CO_2 IAQ surrogate measures indicate a similarly acceptable environment.

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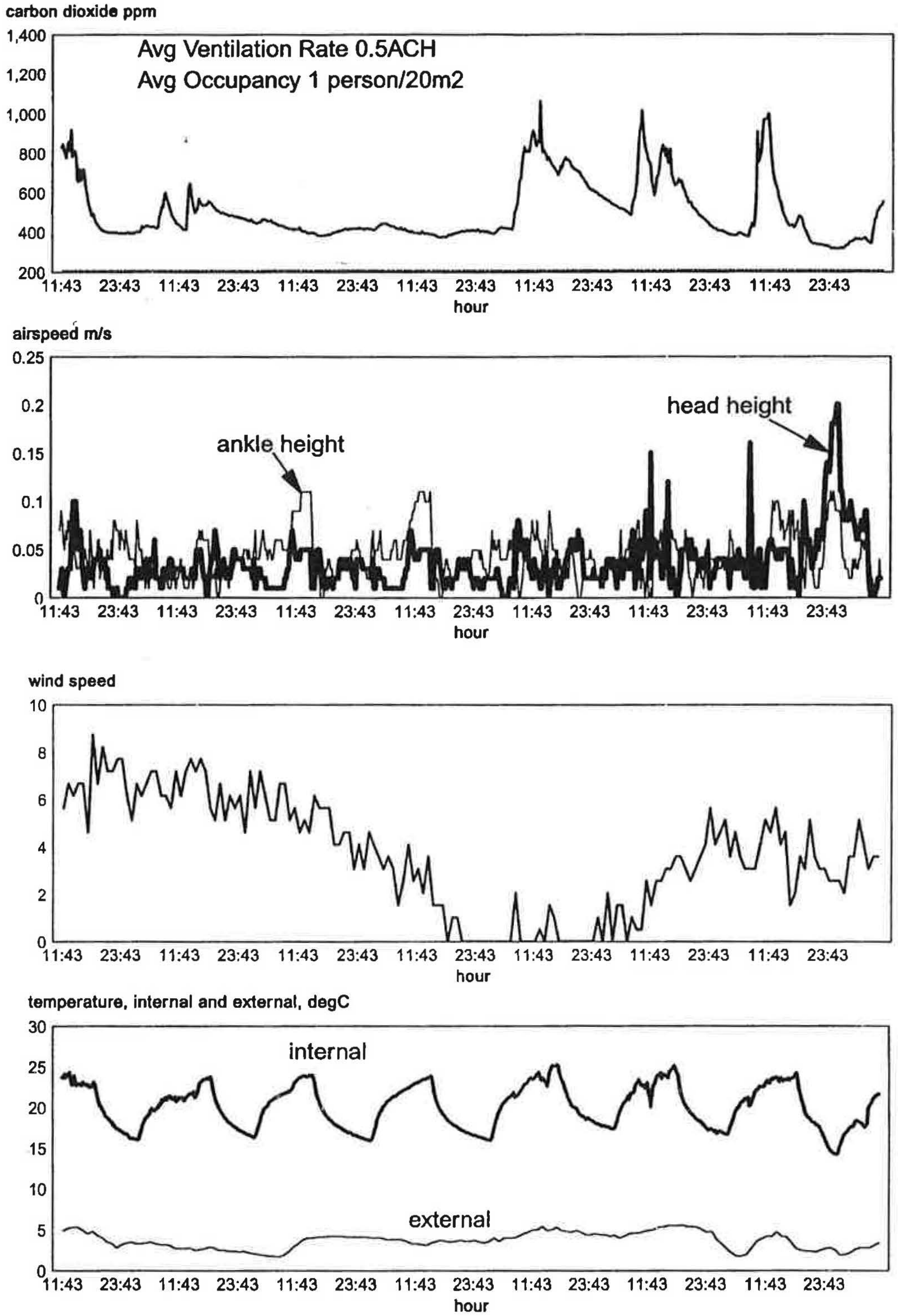

Figure 6 Plot of typical results measured during one week's monitoring in Building 2