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Evaluation of thermal comfort and indoor air quality in offices

THERMAL MODELS BASED ON LABORATORY TESTS AT STEADY STATE CONDITIONS CANNOT ACCURATELY PREDICT THE REAL THERMAL ENVIRONMENT WHERE THE CONDITIONS ARE TRANSIENT AND WHERE OCCUPANTS CHANGE THEIR ACTIVITIES

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Professor Derek Croome and his colleagues in their CIB Montreal paper present the results of an investigation into the indoor environment of a naturally ventilated office and conclude that data from laboratory tests are insufficient. A field test method is established which allows an investigation to take into account window and door opening patterns and peoples reactions to air temperature, fresh air and movement.

Le professeur Derek Croome et ses collègues du CIB Montréal présentent dans leur article les résultats d'une enquête sur l'environnement intérieur d'un bureau naturellement aéré. Ils concluent que les données des épreuves de laboratoire sont insuffisantes. Un système d'essais 'sur le terrain' a été établi, permettant une investigation qui tient compte à l'ouverture des portes et des fenêtres, et aux réactions des occupants à la température, à la fraîcheur et aux mouvements de l'air.

Keywords: air quality, indoor, offices, room comfort, CIB Montreal

This paper presents the results of an investigation into the indoor environment of a naturally ventilated office.

Experiments were carried out to measure the indoor environmental parameters such as air velocity, standard deviation, turbulence intensity and air temperature at several locations, each at three vertical levels. Air change rates for various indoor and outdoor climates were also determined. The concentration of carbon dioxide in the room was monitored. Subjective assessment was made to evaluate the thermal comfort and indoor air quality in the office. The effect of opening windows and the door on the indoor comfort conditions was also investigated.

Regression equations were obtained relating the air change rates to the indoor and outdoor conditions. The turbulence intensity of the room air was found to be dependent on the air change rate. Models were developed for assessing indoor environment based on the field measurements. It was found that Fanger's comfort model overpredicted the neutral temperatures in the room by up to 2K and that in real situations the occupant was more sensitive to the deviation of air temperature from the neutrality than predicted using the laboratory model. The office environment was found to be unsatisfactory both in terms of thermal comfort and indoor air quality. Recommendations are given for improving the indoor environment and reducing the heating costs.

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Introduction

A comfortable indoor environment is a necessity for the occupants' good health and high productivity. The indoor environment is a holistic phenomenon that involves synergy of thermal comfort, indoor air quality, other environmental factors such as the type of building and its psychological relevance for the occupants [1, 2] and energy parameters. Improved thermal comfort is achieved at home or in workplaces through good passive design such as consideration of thermal mass and insulation together with appropriate heating, ventilation or air conditioning systems. The maintenance as well as the design

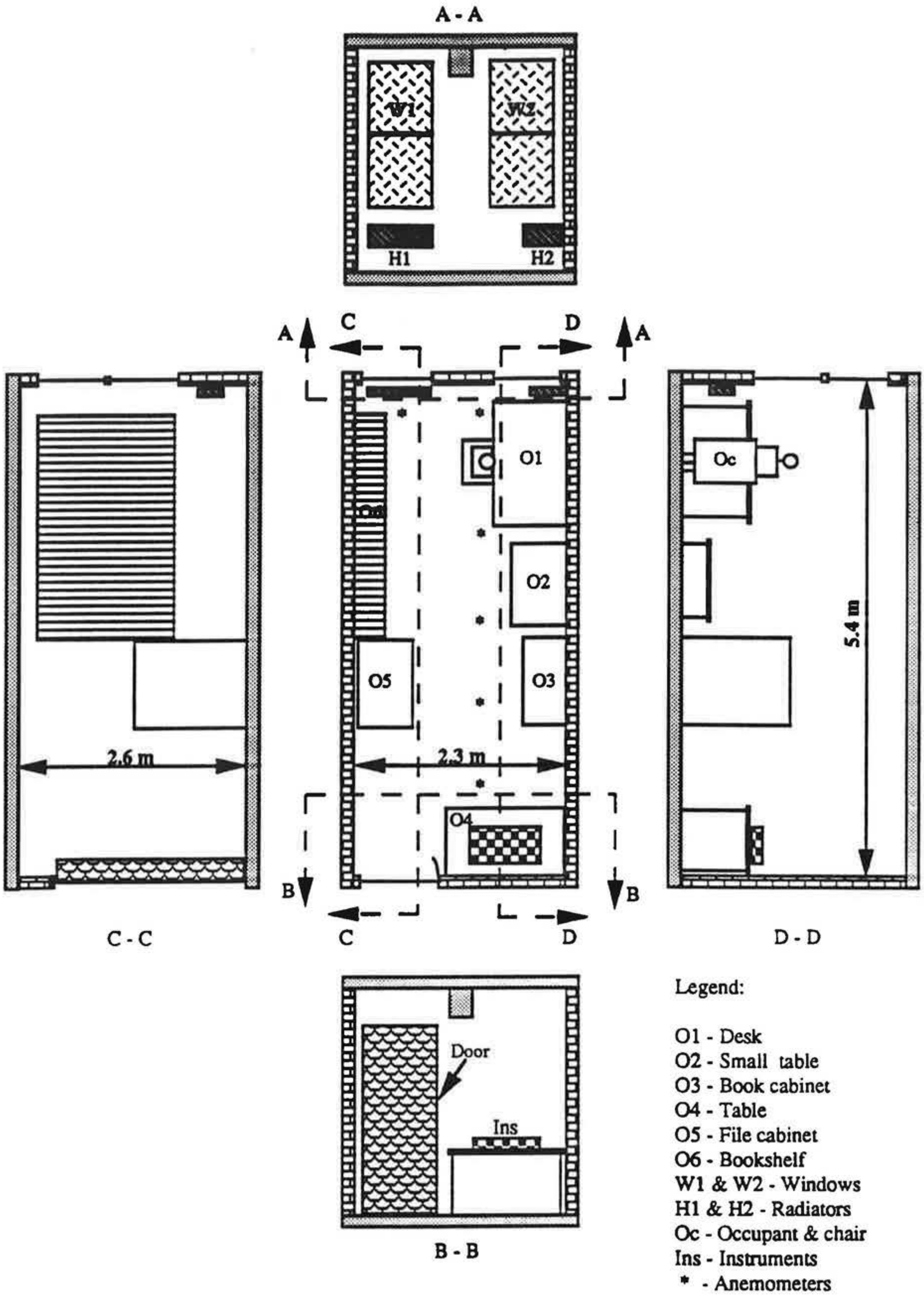

Fig. 1. Schematic of the test room.

of ventilation systems have decisive effects on the indoor environment.

There are some models available for assessing the thermal environment indoors such as thermal comfort indices–Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD)–developed by Fanger [3], which are based on the heat balance between the body and environment and subjective testing in an environmental chamber; these form the basis of ISO 7730 [4]. These models, however, may not be applicable to all the conditions encountered in practice. This is because laboratory subjects are not in their familiar working surroundings and because the comfort depends not only on the quantifiable parameters used for formulating the available models but also on the factors which are difficult to quantify such as job satisfaction, stress, building characteristics and other environmental factors such as light and sound. Dedear and Auliciems [5] concluded from six field studies that factors other than heat-balance variables were involved in determining comfortable or neutral temperatures in natural settings. Schiller *et al.* [6] found that optimum satisfaction with the thermal environment in office buildings was lower than that found under laboratory conditions and suggested that centralized, autonomous environmental systems have substantial inherent limitations in their effectiveness. Unfortunately, a great majority of field studies performed prior to 1984 characterize the thermal environments with sensors at one location near the monitored workstation and recent office building occupant studies have virtually dropped all the physical measurements and used survey methods alone to address a range of environmental parameters [7]. Moreover, most laboratory-based models for assessing the indoor environment are also derived from measured data only to give an overall state of room environment without taking into account non-uniform reactions. For example, there are differences in the sensitivity of different parts of the body to the surroundings especially at head and foot levels. Warm feet and cools head is preferable but many heating systems produce the opposite effect. A more reasonable index for comfort should be able to reflect these differences, which requires detailed measurements of environmental parameters in occupied spaces. Although there is some sophisticated model in which a human body is represented by up to 25 nodes [8], it is also based on the heat balance and is basically designed to calculate the local skin temperatures. Furthermore, most of the investigations on thermal comfort up till now have been carried out under steady state conditions such as those in laboratory tests or for short durations during field surveying. Results from such studies may not fully correspond to normal working situations especially in naturally ventilated offices because the indoor thermal conditions are essentially transient and seasonal due to the changing climate outdoors, varying occupants' activities indoors and variations in the heating and ventilation systems' performance.

Odour intensity is a principal factor defining indoor air quality and has been associated with the level of carbon dioxide [9]. The results of indoor CO_2 measurements have been used to specify minimum ventilation rate requirements. Turner and Binnie [10] in an effort to characterize the major factors influencing air quality in office buildings found that the most significant cause of air quality problems was poor ventilation. Fanger *et al.* [11] carried out an extensive survey of indoor air quality for 20 randomly selected office buildings and assembly halls. It was found that more than 30% of the subjects were dissatified with the indoor air quality, even though the average fresh air ventilation rate was 25l/s per occupant, which is far higher than the recommended value of 7–8l/s per person referred to in the CIBSE Guide and based on the maximum allowable CO_2 level of about 1000 ppm. In order to take into account various sources of pollutants in offices, Awbi [12] advocates increasing the outdoor supply rates to values much higher than the current recommendations so as to minimize complaints from building-related sickness. There is an odour meter now available which permits relative values of odour to be assessed and also senses the total odour arising from several sources [13].

The objective of the present work is to evaluate the indoor environment in naturally ventilated offices for long durations with detailed measurements of the environment parameters and to develop models for assessing the indoor environment based on the field measurements.

Method

This investigation has been carried out by means of physical measurements combined with a subjective assessment of the indoor environment in a naturally ventilated office room over a period of four months in the winter of 1991/92. The office is situated in the north wing of the third level of the FURS building at the University of Reading. It has interior dimensions of 5.4 × 2.3 × 2.6m (length × width × ceiling height). The effective volume of the room, i.e. the volume excluding the space occupied by obstacles, is approximately 29.3m^3. The room is built of one concrete external wall and three concrete brick walls connected to other rooms. The floor is made of prefabricated concrete (carpeted) and the ceiling comprises hardboard layers under the prefabricated concrete roof. The room is connected to the main corridor via a hinged wooden door. There are two weatherstripped double-hung aluminium frame windows in the north face. The office is normally occupied by one person and is heated by two small hot water heated radiators in cold seasons; an extra electric heater is provided when needed for the experiments. A schematic diagram of the room is shown in Figure 1.

Physical measurements

During an experimental test the air velocity, standard deviation, turbulence intensity and air temperature were measured continuously at six locations using thermal anemometers (DANTEC Multi-channel Flow Analyser type 54N10). At each location measurements were taken at points 0.1m (foot/ankle level), 0.6m (centre of gravity of a seated person) and 1.1m (neck/head level of a seated person) above the floor in a vertical line. Measurements were thus made at 18 points in the space. The plane radiant temperature, temperatures of room surfaces and obstacles and indoor air humidity were measured using an indoor climate analyser (Bruel & Kjaer type 1213). Thermal comfort indices (PMV and PPD) were measured using a comfort meter (Bruel & Kjaer type 1212). A CO_2 gas analyser was used for the measurement of indoor CO_2 concentrations.

The air change rate (infiltration rate) for each test was determined using the concentration decay method with an infra-red gas analyser. A portable fan was employed to ensure a good mixing of tracer gas (isobutane) and air in the room for a few minutes after injecting the gas. The wind direction was measured with a wind anemometer and the wind speed with three vane cup anemometers mounted on the top of the building (about 5m above the roof). The outdoor air temperature and humidity were measured using a copper-constantan thermocouple and a hand-held humidity meter respectively.

Table 1. Subjective survey of indoor environment

Date __________; Time __________
Building/Room ____________________
Occupant: Nationality __________; Age ______
Weather:

Please answer the following questions by putting a circle around the appropriate choice.

1. Sex: (a) male (b) female

2. What sort of clothes are you wearing?

Shirt/Blouse:	(a) long-sleeve	(b) short-sleeve
Sweater:	(a) yes	(b) no
Suit:	(a) yes	(b) no
Trousers/Skirt:	(a) thick material	(b) light material
Foot exposure:	(a) exposed	(b) not exposed
Others:		

3. How do you feel the thermal conditions in this room?

Head level	Foot level	Overall
(a) hot	(a) hot	(a) hot
(b) warm	(b) warm	(b) warm
(c) slightly warm	(c) slightly warm	(c) slightly warm
(d) neutral	(d) neutral	(d) neutral
(e) slightly cool	(e) slightly cool	(e) slightly cool
(f) cool	(f) cool	(f) cool
(g) cold	(g) cold	(g) cold

4. How do you feel the air movement in this room?

Head level	Foot level	Overall
(a) too draughty	(a) too draughty	(a) too draughty
(b) draughty	(b) draughty	(b) draughty
(c) acceptable	(c) acceptable	(c) acceptable
(d) stagnant	(d) stagnant	(d) stagnant
(e) very stagnant	(e) very stagnant	(e) very stagnant

5. How strong is the odour?

(a) not detectable
(b) slight
(c) moderate
(d) strong
(e) very strong

6. Do you think the air is fresh?

(a) very fresh
(b) fresh
(c) neutral
(d) slightly stuffy/stale
(e) stuffy/stale

7. Other comments:

Subjective assessment

A subjective assessment was undertaken simultaneously with the physical measurements. The assessment of the thermal environment was based on the occupant's vote on the thermal sensation and air movement in the office under various outdoor or indoor conditions and different arrangements of window and door openings. This assessment was made based on judgements at head and foot levels as well as for overall comfort. The indoor air quality was assessed according to the impressions of odour and freshness of air. A seven-point thermal sensation scale was used to evaluate thermal sensation and a five-point scale to rate the impressions of comfort with regard to air movement, odour intensity and air freshness. A sample questionnaire for subjective assessment is shown in Table 1. Each questionnaire reflected the occupant's impressions of the indoor environment for a whole working day.

Results and discussion

In all 46 tests were performed. The results are discussed in two parts–environmental parameters and subjective evaluation.

Table 2. Opening area and constants for Equation 4

Window/door arrangement	A	a_1	a_2	b	c
Window open only	A_w	388	−435	15	3
Window and door open	$A_w A_d/\sqrt{(A_w^2 + A_d^2)}$	60059	−61481	103	0
Door open only	A_d	0	0	0	15

Environmental parameters

This includes all the measured results for air change rate and for other variables concerning the room environment.

Air change rate

The air change rate was determined for every test. However, the first four results were discarded due to overcharging of the tracer gas which resulted in a nonlinear relation between the concentration of the gas and time on a semilog scale. Of the remaining 42 valid results, 22 were obtained for the cases when all the windows and door were closed, 11 for the cases when one of the windows was partly open while the door remained closed, four for the cases when one of the windows and the door were partly open and five for the door partly open but the windows closed.

The total air infiltration into a room, Q, is generally considered the combined effect of wind and stack and the combination is in the form of quadratic addition [14]:

$$Q^2 = Q_w^2 + Q_s^2 \qquad (1)$$

The infiltration rate due to wind, Q_w, is proportional to wind speed whereas the infiltration rate due to stack, Q_2, is approximately proportional to the square root of the temperature difference between indoors and outdoors. Therefore, the air change rate for the windows and door closed is assumed dependent on the wind speed and indoor–outdoor temperature difference in the following form:

$$N^2 = aV_w^2 + b\Delta T \qquad (2)$$

where N = air change rate (h^{-1}); v_w = wind speed (m/s); ΔT = indoor–outdoor temperature difference (K).

The indoor temperature was taken as the average of temperature readings of the thermal anemometers distributed in the room. The coefficients a and b in Equation 2 were derived using a multilinear regression method as follows: $a = 0.0393$ and $b = 0.0154$. The regression has a correlation coefficient (adjusted for all the multiple correlations in this work) of 0.98 and a confidence level of almost 100%. The wind speed ranged from 0.2 to 10.0m/s and the range of the indoor-outdoor temperature difference was between 9.7K and 20.4K.

By taking the partial derivatives of N with respect to V_w and ΔT in Equation 2 and setting their ratio as unity one gets

$$\frac{\partial N}{\partial V_w} \bigg/ \frac{\partial N}{\partial \Delta T} = \frac{2aV_w}{b} = 1 \qquad (3)$$

That is to say, at a critical point of $V_w = 0.2$m/s, the variation in the wind and stack has the same effect on the air change rate. When V_w is greater than 0.2m/s, wind speed plays a more important role in the variation of air change rate than the stack does, and *vice versa*. Since the measured wind speed for these cases was not less than this critical value, it may be concluded that the wind speed is the main factor that brings about the fluctuation in the air change rate when all the windows and door are closed.

The air change rate for a window and/or the door partly open is correlated as

$$N^2 = [a_1 + a_2|\sin(90 - \theta/2)|](V_w A)^2 + b\Delta T A^2 + c \qquad (4)$$

where θ = wind direction, degree from north clockwise; A = opening area of window (A_w) and/or door (A_d) (m^2). The calculation of the area A and the constants a_1, a_2, b and c are shown in Table 2.

The correlation coefficients and confidence levels are respectively 0.94 and 99.5% for a window partly open and 1.00 and 90% for both a window and the door partly open. The confidence level for the latter is low due to insufficient

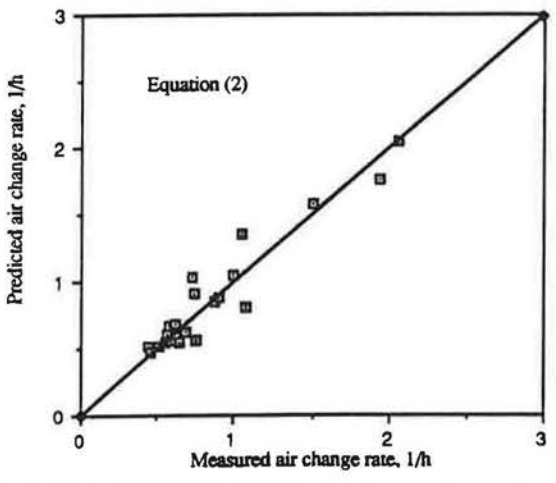

Fig. 2. Scattergram of the measured against predicted air change rate with windows and door closed.

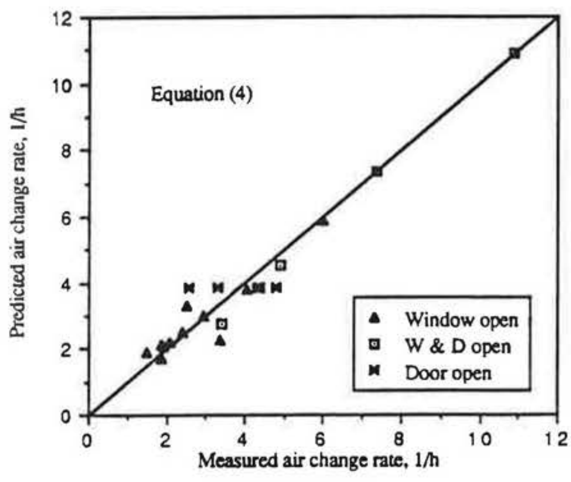

Fig. 3. Scattergram of the measured against predicted air change rate with windows and/or door partly open.

Outdoor conditions: temperature from −0.2 to 13.6°C; wind speed from 0.2 to 10.0m/s

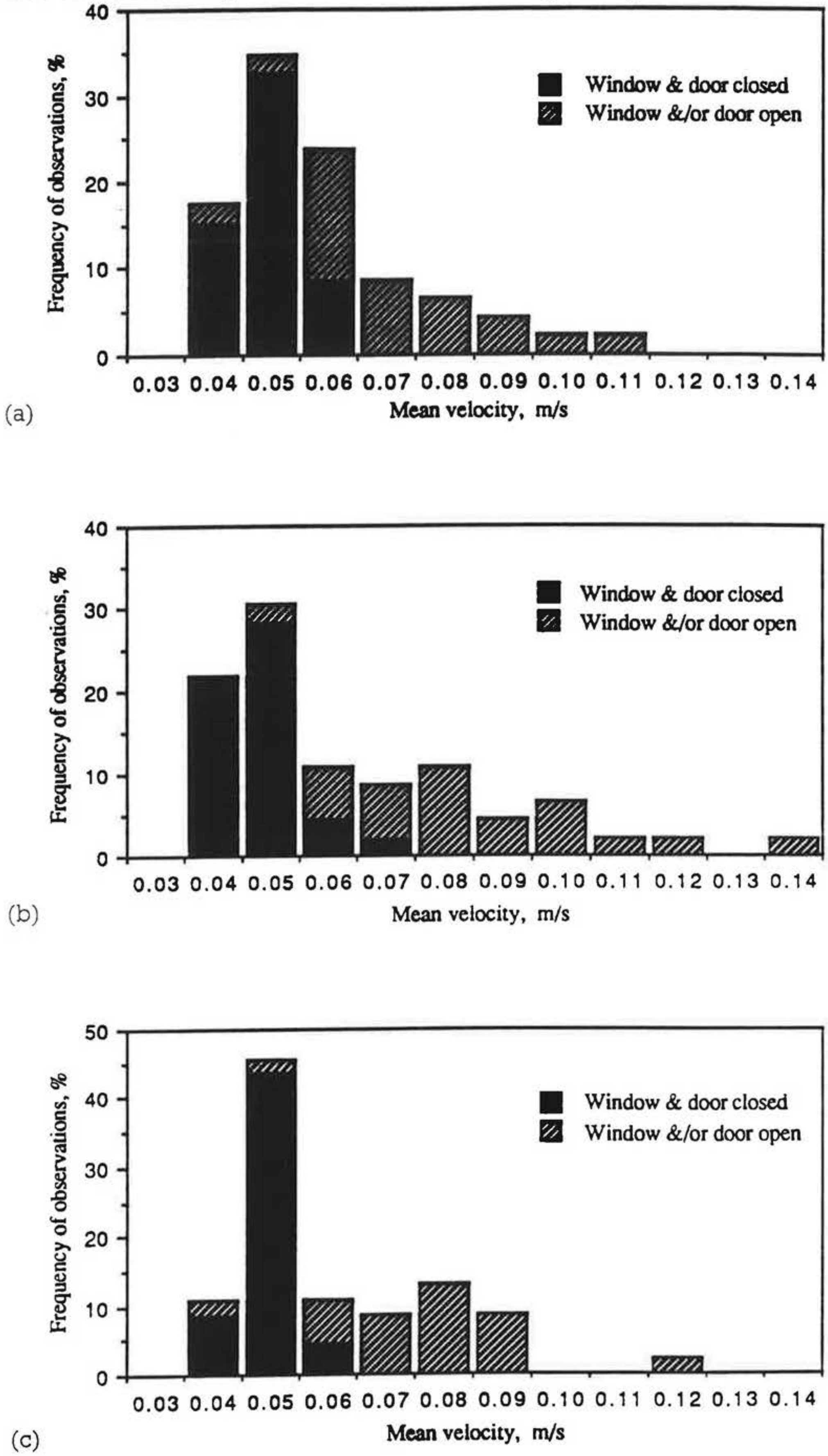

Fig. 4. Frequency distribution of mean air velocity at (a) head level; (b) foot level; (c) overall.

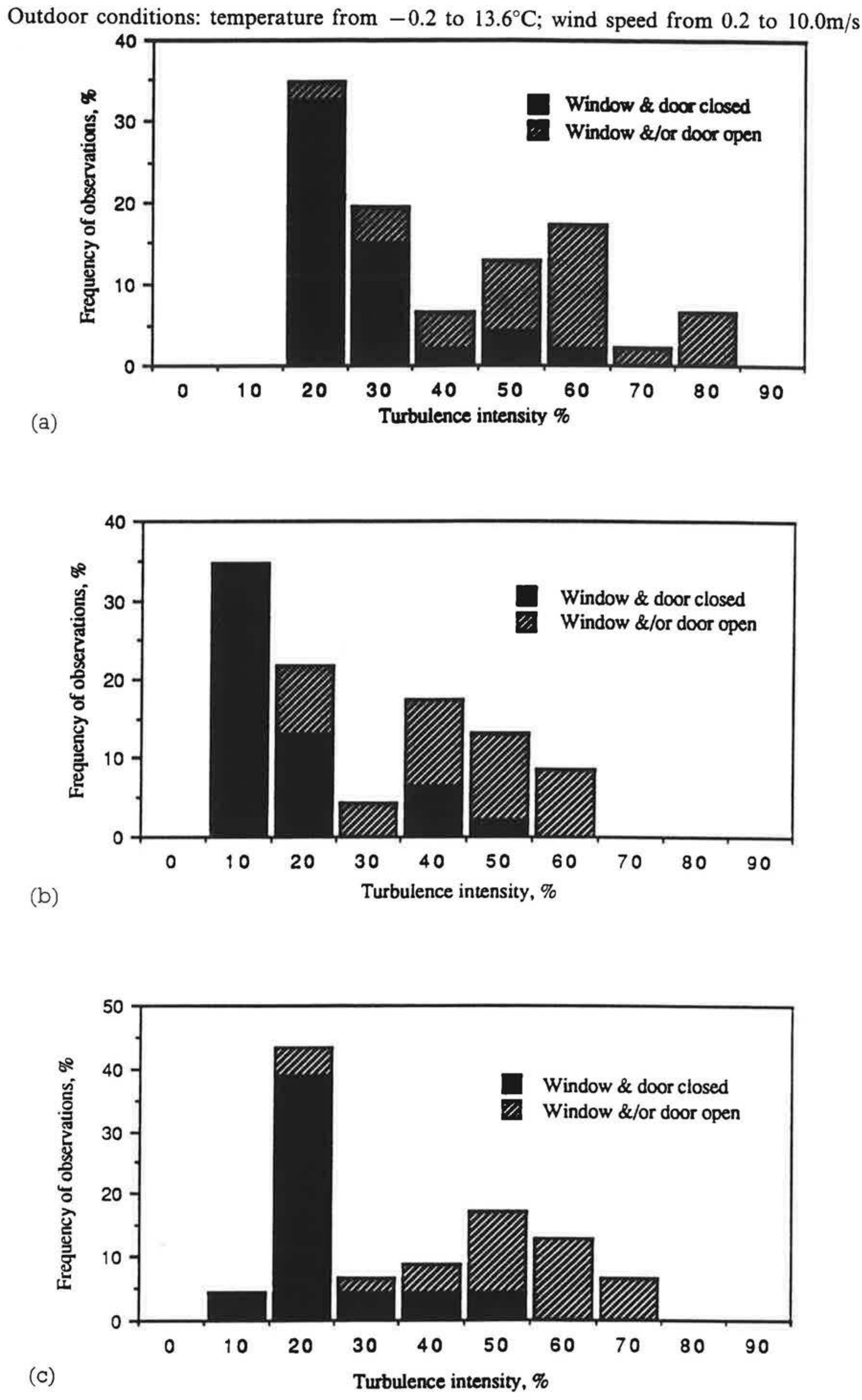

Fig. 5. Frequency distribution of turbulence at (a) head level; (b) foot level; (c) overall.

Outdoor conditions: temperature from -0.2 to 13.6°C; wind speed from 0.2 to 10.0m/s

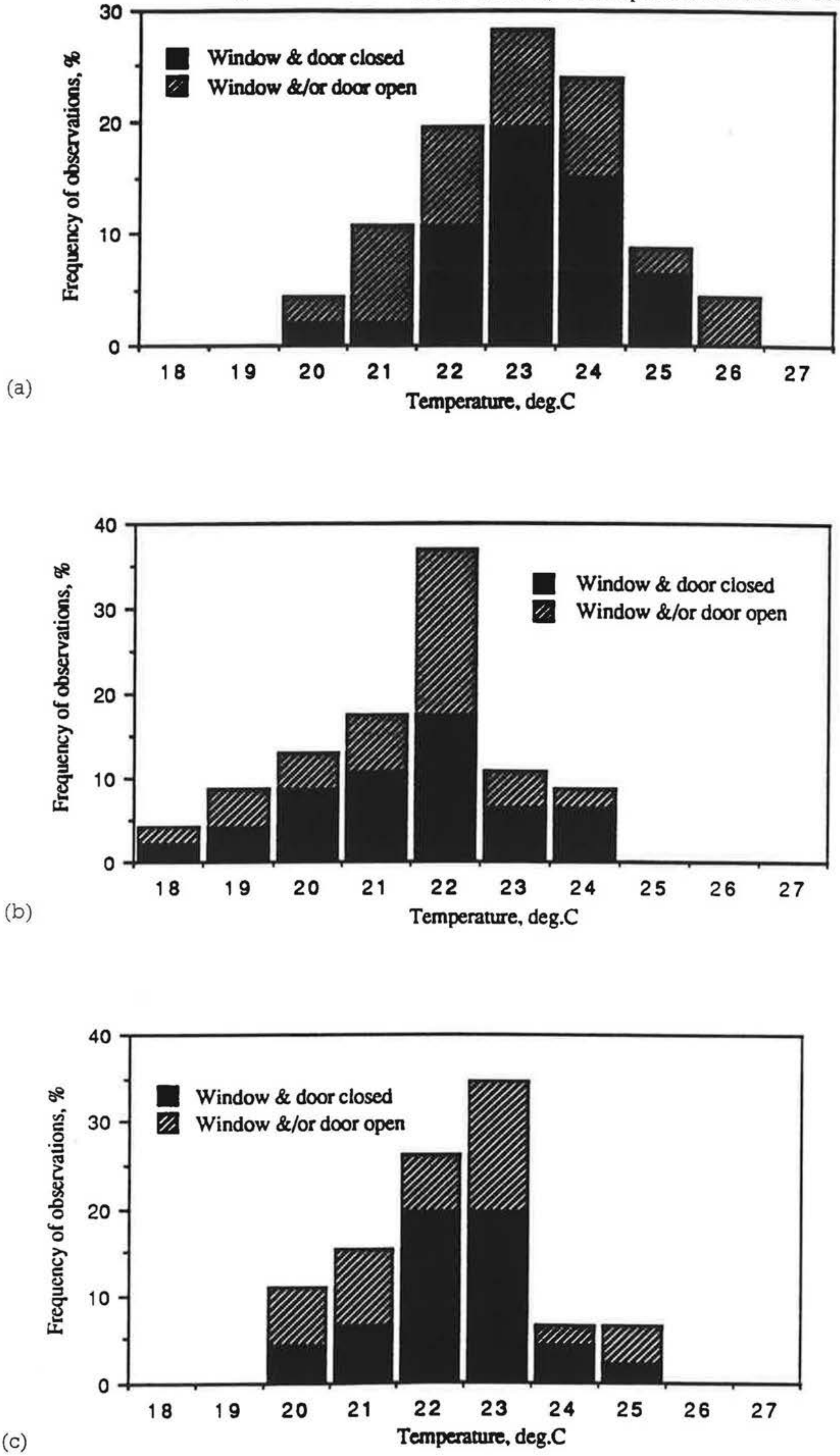

Fig. 6. Frequency distribution of air temperature at (a) head level; (b) foot level; (c) overall.

Table 3. Distribution of room environment

	Mean air velocity			Turbulence intensity			Mean air temp.		
	Head	Foot	Overall	Head	Foot	Overall	Head	Foot	Overall
Min	0.038	0.041	0.042	16.2	7.7	14.0	20.1	17.8	19.7
Max	0.113	0.136	0.115	79.1	63.9	68.2	26.2	24.0	24.9
Mean	0.059	0.064	0.060	39.4	28.7	34.7	23.1	21.4	22.4
S.d.	0.017	0.023	0.017	18.9	17.2	18.3	1.4	1.5	1.4

data points and the correlation should be used with caution. The air change rates for the cases when only the door was partly open could not be satisfactorily correlated with the outdoor environmental parameters. It appears that for this kind of arrangement of window/door opening the air change rate was influenced more by the conditions in the corridor than by the outdoor environment. The constant in Table 2 for this arrangement was calculated from the mean value of the measured air change rates in order to fit the form of the correlation. Since opening the door only or opening both the window and door in this office was not a normal practice in winter, only a few tests were performed for comparison. The window opening area for the tests performed ranges from $0.036m^2$ to $0.194m^2$. The level of door opening is between slight ($0.24m^2$) and half ($1.20m^2$). The air change rates for the opening areas beyond these ranges need further exploration particularly in warm seasons.

Figures 2 and 3 show the scattergrams of the measured air change rates against predicted values using Equations 2 and 4 respectively. When all the windows and door were closed the infiltration rates ranged from about $0.44h^{-1}$ for a mild and still outdoor climate to $1.94h^{-1}$ for a very windy day with a mean of $0.86h^{-1}$ or 7l/s, which is slightly lower than the minimum fresh air requirement to maintain a CO_2 concentration maximum limit of 1000ppm. When a window and/or the door were partly open, the air change rate increased dramatically depending on the opening size, the wind direction, the wind speed and the indoor–outdoor temperature difference. The air change rates under the circumstances investigated ranged from $1.51h^{-1}$ to $5.88h^{-1}$ for a window partly open, 3.40 to $10.87h^{-1}$ for both the window and door partly open and 2.56 to $4.79h^{-1}$ for only the door partly open.

Room environment

The physical data for the room environment were obtained for every test. Figures 4 to 6 show the relative frequency distributions for mean air velocity, turbulence intensity and mean air temperature at head level, foot level and overall for the room (mean of three heights) respectively. In these figures the data were divided into two categories according to whether all the windows and door were closed or not.

As seen from Fig. 4 when the windows and door were closed, the mean air velocity in the room was very low with an average of about 0.05m/s. The air velocity was not apparently influenced by the air change rate. In some cases, for instance, as the air change rate increased the mean air velocity decreased rather than increased. Besides, the air velocity at foot level was slightly higher than that at head level. However the difference between them was not significant. When a window and/or the door were partly open, the velocity increased but not very much, with an average value still being less than 0.15m/s.

Figure 5 indicates that when the windows and door were closed the turbulence intensity for most of the days was between low and moderate with a mean of 22.5%. When the window and/or door were open, the mean of turbulence intensity was increased to 42.0%. According to Melikov *et al.* [14] the magnitude of turbulence intensity increases with the decrease in the mean air velocity. However, a regression analysis indicates that the correlation between the turbulence intensity and mean air velocity is insignificant especially for the data at foot level. The turbulence intensity appears better to be correlated to the air change rate. The best fit of the correlation is

$$Tu = 25.76N^{0.42} \quad (r = 0.68) \tag{5}$$

where Tu is the turbulence intensity in percentage.

The indoor air temperature changed from day to day during the course of measurement, ranging from 17.8°C to 26.2°C with a mean of 22.4°C (Fig. 6) due to the fluctuations of outdoor temperature ranging from −0.2°C to 13.6°C, air change rate and heat loss or gain from the room and due to opening the window or door. Temperatures above 25.5°C resulted from the heat provided by the personal electric heater which was used when a window alone, or together with the door, was partially open, to compensate for the ventilation heat loss. In some of these tests the room was overheated because of the mild outdoor climate. It can also be seen from Figure 6 that the air temperature at head level is higher than that at foot level with a mean vertical temperature difference of 1.6K. A large temperature stratification was observed in some of the tests with the vertical temperature difference as high as 3.6K which is greater than the ISO limit for comfort (the vertical air temperature difference between 1.1m and 0.1m above the floor not to be greater than 3K).

The room surface temperatures were usually lower than the mean air temperature especially for the north wall which was directly exposed to the cold ambient. The measured plane radiant temperature, and thereby the calculated mean radiant temperature, were also lower than the mean air temperature. In some cases when both the window and door were opened the air temperature was lower than the radiant temperature due to a large influx of cold air. The average difference between the mean air temperature and mean radiant temperature for all the tests was 0.6K.

The relative humidity in the room throughout the test period was normally within the comfort limits, ranging from 40% to 55% with a mean of 46%. On some occasions it dropped to slightly below 40%, the lower limit for comfort, but no discomfort due to this was observed.

Table 3 summarizes the distributions of the room environmental data measured with the thermal anemometers.

Subjective evaluation

Out of 46 tests, 44 subjective measurements were collected. Figures 7 to 9 present the distributions of votes over space and time for one subject on thermal sensation, air movement, odour intensity and air freshness. The rating scales for these parameters are shown in Table 4.

Thermal sensation

The distribution of votes on thermal sensation at different levels is shown in Fig. 7. When the windows and door were closed the mean thermal sensation was on the warm side of neutral. When the window and/or door were opened, the votes were scattered widely over the thermal sensation scale, with votes for the cool side being roughly the same as those for the warm side. However, the measured PMV values, which were obtained from Fanger's comfort equation, for the corresponding tests were close to the neutral point for most of the test conditions. This suggests that in the present investigation Fanger's equation underestimates the thermal impressions for the cases when the windows and door were shut and under-values the swings of the impressions for these and other cases. This may be due to three main reasons. One is the assumption of steady state laboratory conditions used in the derivation of Fanger's equation. Another is the over-simplification of the metabolic rate of the occupant. The occupant rarely sat in the room for a long period, say one hour, without moving around or engaging in other activities such as teaching. The metabolic rate was, however, taken as a constant (1.2 met) in the calculation of PMV due to the difficulty in measuring its exact value. The third reason is the sensitivity of PMV to clo values. In a laboratory test the clo values are consistent whereas in field tests the clothing levels vary with occupants. In this case there is only one subject, hence the clo value is easy to estimate but varies with time as a suit may be worn or not worn.

The thermal sensation was in general dependent on the room air temperature and velocity. The regression equations for the thermal sensation (TS) at head level, foot level and overall for the room against mean air temperature (T in °C) and velocity (V in m/s) are respectively

head $\quad \mathrm{TS} = 0.5732T - 11.97\sqrt[4]{V} - 6.93 \quad (r = 0.66) \quad$ (6a)

foot $\quad \mathrm{TS} = 0.5624T - 7.53\sqrt[4]{V} - 8.28 \quad (r = 0.63) \quad$ (7a)

overall $\quad \mathrm{TS} = 0.6146T - 12.27\sqrt[4]{V} - 7.46 \quad (r = 0.68) \quad$ (8a)

When the data were separated into the two categories, one for all the windows and door shut and the other for a window and/or the door open; the effect of air velocity was found not to be significant. Hence the following simplified equations have been given as (in the order of head level, foot level and overall):

for the windows and door closed

head	$\mathrm{TS} = 0.4055T - 8.54$	$(r = 0.52)$	(6b)
foot	$\mathrm{TS} = 0.5224T - 10.84$	$(r = 0.67)$	(7b)
overall	$\mathrm{TS} = 0.4815T - 10.13$	$(r = 0.62)$	(8b)

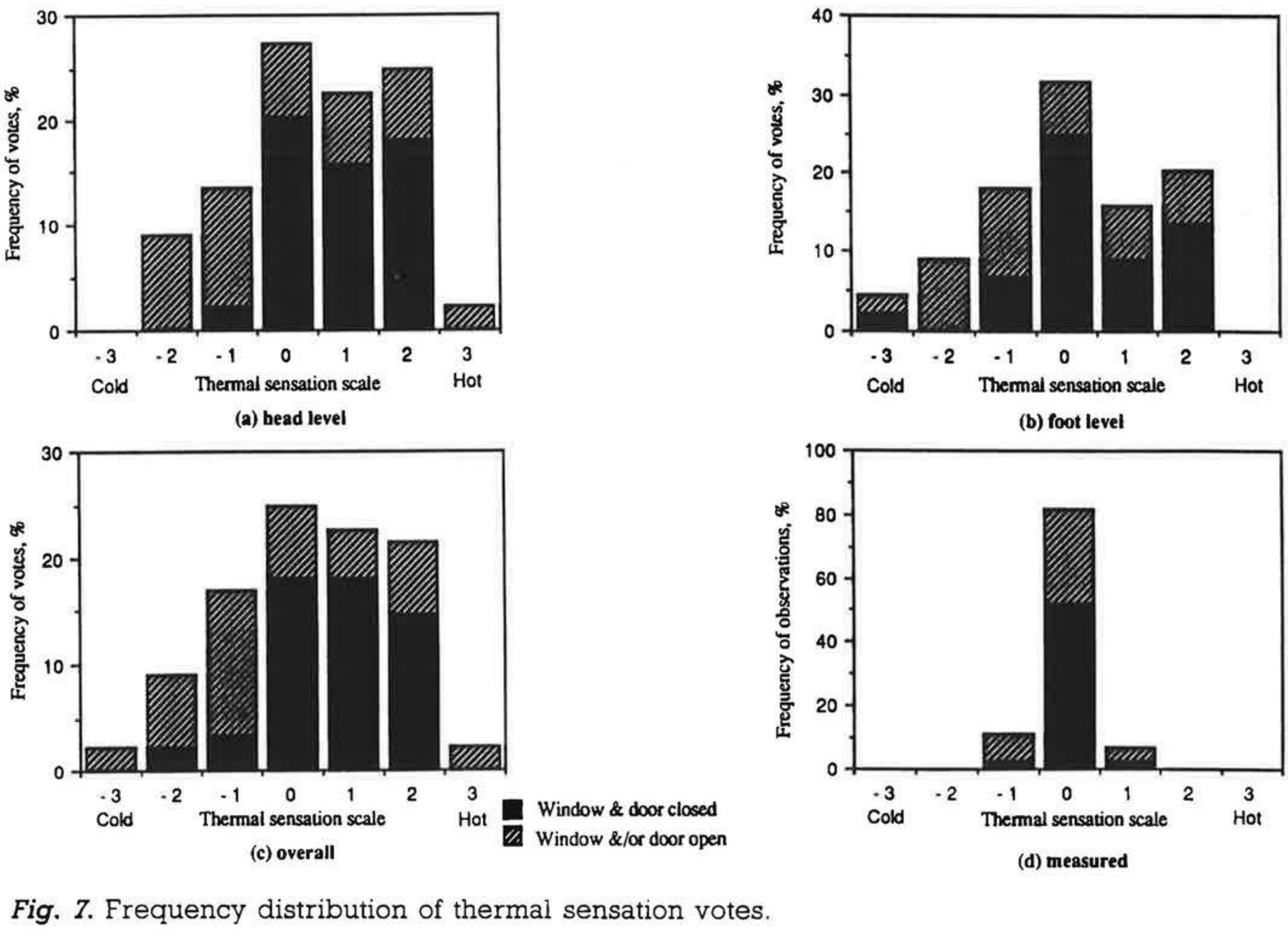

Fig. 7. Frequency distribution of thermal sensation votes.

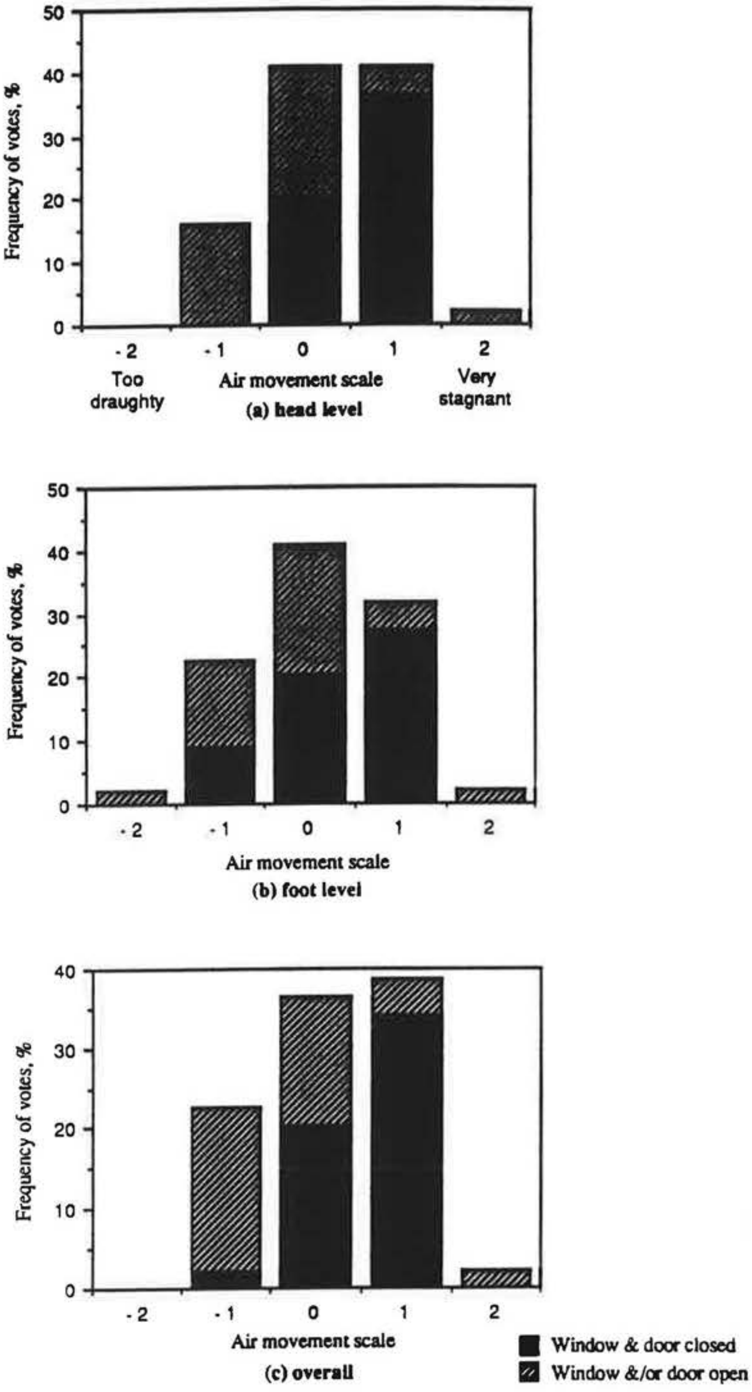

Fig. 8. Frequency distribution of air movement votes.

for a window and/or the door open

head	$TS = 0.7024T - 16.20$	$(r = 0.70)$	(6c)
foot	$TS = 0.6939T - 15.26$	$(r = 0.62)$	(7c)
overall	$TS = 0.8371T - 18.95$	$(r = 0.72)$	(8c)

All these correlations have confidence levels of 99.5% or above.

In Figure 10 the occupant's thermal sensation responses are presented as a function of mean air temperature, using a mean air velocity of 0.06m/s for Equations 6a, 7a and 8a. The PMV curve predicted from Fanger's equation is also presented for comparison (assuming a metabolic rate of 1.2met and a clo value of 0.8). From the above equations or the corresponding curves in Figure 10 the neutral temperatures (T_n), i.e. T for $TS = 0$, can be obtained. The neutral temperature predicted from Fanger's comfort equation is the air temperature for PMV equal to zero. Note that the curve from Fanger's equation is theoretically not a straight line but because the curvature is very small, then the error caused by linearising the curve is negligible in the region close to the comfort temperature. The deviations in the neutral temperature between Fanger's equation and the field measurements can be calculated. The neutral temperature predicted from Fanger's equation is 22.8°C for air velocities between 0.05 and 0.075m/s. The calculated neutral temperatures from the above equations together with the difference in neutral temperature, ΔT_n, between Fanger's equation and Equations 6, 7 and 8 are shown in Table 5.

It can be seen from Table 5 that Fanger's equation generally overpredicts the neutrality especially for the cases when the windows and door were closed due to various reasons mentioned above, which seems to

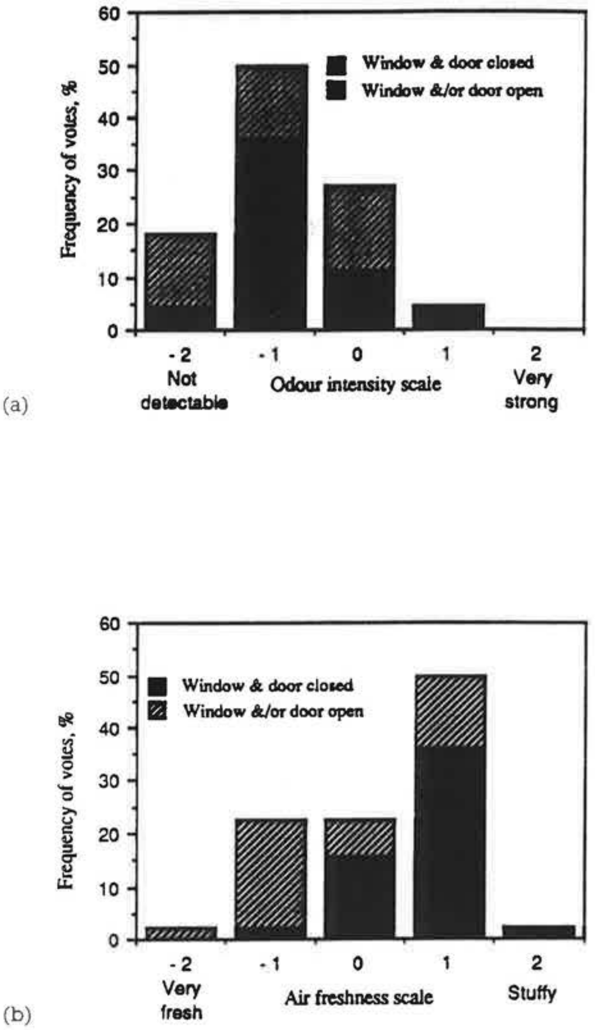

Fig. 9. Frequency distribution of (a) odour intensity votes; (b) air freshness votes.

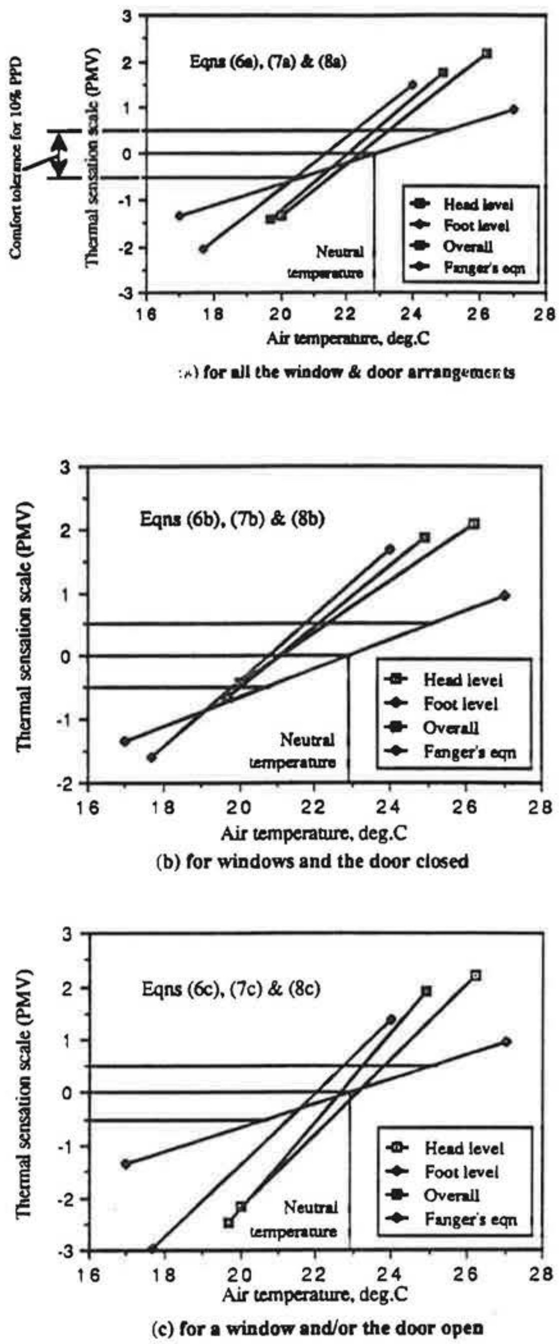

Fig. 10. Effect of air temperature on thermal sensation responses.

confirm the findings by Schiller *et al.* [6]. A more obvious and important point is that from the present investigation the correlated curves in Fig. 10, in particular the ones for a window and/or the door open, are steeper than those given by Fanger's equation, suggesting the occupant is more sensitive to changes of air temperature. This fact was also observed by Fishman and Pimbert [15] whose field study showed that the steepness of the slope of the curve from the observations deviated from Fanger's equation particularly at temperatures above 24°C. In addition they also found that Fanger's comfort equation predicted the neutral temperature 0.6K higher than that from the field survey, which was attributed to the incorrect estimation of the subjects' clothing. The deviation appears to be more at foot level than at head level.

Table 4. Rating scales for thermal sensation (TS), air movement (AM), odour intensity (OI) and air freshness (AF)

Rating	TS	AM	OI	AF
−3	cold			
−2	cool	too draughty	not detectable	very fresh
−1	slightly cool	draughty	slight	fresh
0	neutral	acceptable	moderate	neutral
1	slightly warm	stagnant	strong	slightly stuffy
2	warm	very stagnant	very strong	stuffy
3	hot			

Table 5. Neutral temperatures from the field measurements compared with Fanger's value of 22.8°C

Equation	(6a) Head	(7a) Foot	(8a) Overall	(6b) Head	(7b) Foot	(8b) Overall	(6c) Head	(7c) Foot	(8c) Overall
T_n (°C)	22.4	21.4	22.0	21.1	20.8	22.1	23.1	22.0	22.6
ΔT_n (K)	0.4	1.4	0.8	1.7	2.0	0.7	−0.3	0.8	0.2

It is also noted that the neutral temperature for the head level is between 0.3K and 1.1K higher than that for the foot level. This seems to disagree with the common belief concerning the comfort requirement of warm feet and cool head. The reason for this disagreement may be the adaptation of the occupant to the neutrality, i.e. the occupant adjustment to the surrounding temperature. In this case, the subject concerned is the normal sole occupant of the room and could have been accustomed to his usual environment and hence tolerated a slight vertical temperature difference. This is shown by the fact that most of the thermal sensation votes indicate a nearly uniform room environment despite that there was always a positive vertical temperature difference. In some instances, of course, a local discomfort of either cold feet or warm head was observed when the vertical temperature difference was excessive. As mentioned before, the average vertical temperature difference is 1.6K. If the subject had not been the normal sole occupant and had been used to an environment without such a temperature stratification, it can be postulated that he may have voted the thermal sensation for neutral temperature difference otherwise, namely, the neutral temperature at foot level to be 0.5K to 1.3K higher than that at head level.

If according to Fanger's definition the central three categories of the thermal sensation scale were regarded as an indication of an acceptable state for thermal comfort whereas the votes outside these central categories were considered to represent dissatisfaction with the thermal state, the results suggest that about one-third of the reponses were dissatisfied with the thermal environment whether for head, or foot or overall impressions. Most of the dissatisfaction that occurred when the windows and door were closed was caused by overheating, which could be avoided simply by controlling the heat output from the emitters if a thermostat was available or by window opening. On the other hand, because the overall votes were on the warm side and the amount of heat supply could not be decreased in mild climates the heating costs could be reduced with the help of a thermostat or a weather compensated heating system. A great majority of the votes on the cool side occurred when a window was opened either alone or in combination with the door, in order to evaluate the effect of the opening on the indoor environment. In practical situations the window would be closed or the size of the opening would not be so large when it was cold outside.

Air movement

Figure 8 shows the frequency distribution of air movement votes. The overall impression of the air movement in the room for the cases when the windows and door were closed was on the side of being stagnant. When a window and/or door were partly opened, the impression shifted to being slightly draughty. The measurements showed that there was little air movement when the windows and door were closed. Even when a window and/or the door were partly opened the mean air velocity at the measured points were still below 0.15 m/s. Since the feeling of draught at a comfortable room temperature is strong only when the air velocity is above, say, 0.25 m/s or, to a lesser extent, at a high turbulence intensity, the response to draught in certain instances must have been the consequence of too low a room air temperature and/or too high a turbulence intensity. However, when the draught was detected the thermal sensation was rated as cold especially at foot level, implying that low temperature was the main source of the draught.

The ratings of the air movement (AM) are associated with the air temperature, velocity and turbulence intensity as follows:

$$\mathrm{AM} = 0.1462T - 20.31V - 0.0048Tu - 1.71 \qquad (r = 0.57) \quad (9)$$

at head level;

$$\mathrm{AM} = 0.2037T - 6.65V - 0.0081Tu - 3.64 \qquad (r = 0.44) \quad (10)$$

at foot level;

$$\mathrm{AM} = 0.1455T - 18.99V - 0.0069Tu - 1.69 \qquad (r = 0.56) \quad (11)$$

for the room as a whole.

The above equations indicate that the draught risk increases (i.e. AM decreases) with an increase of air velocity and turbulence intensity but with a decrease in air temperature. A 'comfortable' temperature for air movement, defined as the air temperature for the rating of air movement as acceptable, can be obtained from these equations for given air velocity and turbulence intensity. By substituting the mean values of velocity and turbulence intensity for the test conditions ($V = 0.06$m/s; $Tu = 34.7\%$) the comfortable temperature is calculated to be 21.1°C for the head level, foot level and overall judgement, which is approximately equal to the neutral temperature at foot level and is 1°C lower than that at head level when all the cases were taken into consideration. The inference is that when the room environment is comfortable in terms of warmth at foot level it is also acceptable for air movement. If the indoor climate is such that the thermal sensation is comfortable at head level but slightly warm at foot level the occupant will feel slightly stuffy. Therefore sometimes a compromise between the requirements for warmth and air movement may have to be made to achieve an acceptable thermal condition.

Figure 8 and Equations 9 and 11 also indicate that the overall impression of air movement is similar to that felt at head level, i.e. when the head feels stagnant the overall response of the air movement will be stagnation; this is also true for draught at head level and overall impressions. Moreover, these two equations indicate that an increase in mean velocity of about 0.05m/s can change air movement judgement, say, from being slightly stagnant to acceptable at head level or overall judgement. Since most of the votes were slightly stagnant for air movement and slightly warm for thermal sensation when the windows and door were closed, to increase the velocity from 0.05m/s to 0.10m/s would give a more pleasant thermal environment for the office. In these tests the feet were more sensitive to air temperature but less sensitive to air velocity than the head. Since the velocity at foot level is slightly higher and the votes on stagnant air are fewer than those for the head level, less or no increment in the velocity is necessary to attain a comfortable condition. The effect of turbulence intensity on the air movement is marginal compared with air velocity or temperature.

Fanger *et al.*[16], based on the laboratory testing, derived the following equation for the calculation of the percentage of dissatisfaction due to draught:

$$PD = (3.143 + 0.3696VTu)(34 - T)(V - 0.05)^{0.6223} \quad (12)$$

if $V < 0.05$m/s insert $V = 0.05$m/s.

According to this model the draught risk for all but one test was found to be negligible as the calculated percentage of dissatisfied using the measured mean air velocity, turbulence intensity and mean air temperature is within the 10% draught risk criterion. The only exception was the one when a window was opened at the maximum size of the test range on a cold day which led to an indoor air velocity over 0.10m/s and temperature around 20.0°C. Again, the laboratory model fails fully to predict the comfort in practice because it underestimates the effect of air velocity. Equation 12 indicates that the draught risk is small at a velocity close to 0.05m/s whatever the magnitude of air temperature or turbulence intensity is. In reality at a low indoor temperature air close to the exposed parts of the warm human body would form a free convection current as a result of thermal buoyancy such that the velocity of air flowing over the head of a standing subject could reach 0.3m/s [17]. Using the air temperature and velocity near the body, Equation 12 might show the presence of draught. However, the model equation was derived on the basis of the measurements taken at such a distance away from the body that the temperature and velocity were undisturbed by free convection currents. Therefore it may be inferred that the model is not applicable to the circumstances where both air temperature and velocity are lower than those recommended for thermal comfort. This model also fails to take into account the need for high velocities in densely occupied spaces and also where humidity may be high.

Odour intensity

Odour was detectable in most cases when the windows and door were closed and was rated as being slight (see Figure 9). The measurement of CO_2 levels indicated that its concentration was normally well above the criterion of 1000ppm with occupancy at low air change rates. Even when the air change rate was higher than 10l/s, the CO_2 level was not much lower, suggesting that some of the air infiltrated from the corridor was not fresh at all but rather contaminated air exhausted from other rooms, especially classrooms on the lower floor of the building. Further evidence for this is that sometimes the CO_2 level was noticeably high (about 500ppm indoors compared to 300ppm outdoors) even though the room was not occupied. However when a window was partly opened the odour was reduced, or not detectable, and the CO_2 concentration was around 600–1000ppm during occupancy depending upon the total air change rate. But, when the door alone or together with a window was open the odour did not always disappear or decrease due to the diffusion of contaminated air from the corridor.

No satisfactory correlation between odour intensity and CO_2 level or air change rate could be established for the present investigation. In some cases when the CO_2 level was low, or the air change rate was high, the odour was still perceivable while the other cases where the CO_2 level was higher than 1000ppm the odour intensity was rated as not detectable. This seems to suggest that there were other pollution sources such as building materials or furnishings which could be more significant than the CO_2 emission from the occupant which could have partly contributed to the odour in the room. Also the judgement could be affected by fatigue of the olfactory sense.

Air freshness

Figure 9 also shows that the rating of air freshness was in general slightly stuffy when the windows and door were shut regardless of the variation in the infiltration rate. It appears that the amount of outdoor air entering into the room may not be as significant a factor that influences the air freshness as is generally supposed; this was also pointed out by Rodahl [19]. For these test conditions, the air was rated as fresh only when the air temperature was lower than neutral temperature. This confirms the observations by Bedford [20] who pointed out that a cool room tended to feel fresh and an overheated one, stuffy. Bedford also considered that the impressions of freshness were due to the local stimulations of the skin by the environment partly thermal and partly tactile. The impressions of stuffiness at comfortable temperatures may have been attributed to the low air velocities in the room because when a window was partly open, the air was often rated as fresh. When only the door was open, air was not fresh but slighlty stuffy and corresponding responses were obtained for odour intensity. The opening of the door is thus not a proper way to improve the indoor air quality in this particular case.

Air freshness, ignoring the cases for opening the door only, can be related to the air temperature, velocity and turbulence intensity in the following relationship:

$$AF = 0.0863T - 19.37V - 0.0130Tu \qquad (r = 0.66) \quad (13)$$

Equation 13, which has a confidence level over 99.5%, indicates that air freshness increases when air temperature decreases; or when air velocity or turbulence intensity increases. A decrease in temperature of 11°C or an increase in velocity by 0.05m/s or in turbulence intensity by 80% would raise the freshness voting by one unit. According to this relation, the most effective means to improve the air freshness is to increase air velocity and it is the only realistic way to upgrade the freshness by one unit for this office. A combined effect (e.g. decreasing air temperature and increasing air velocity) may be feasible to meet the requirements for air freshness and other comfort indices such as warmth and draughtiness.

Summary

From the subjective assessment of the indoor environment it seems that for the existing room structure a window should be opened or other suitable vent provided to introduce fresh outdoor air even in winter if a comfortable indoor environment is to be provided. The size of the opening should be adjusted according to the outdoor climate. However, when the outdoor air is cold extra heat supply (preferably adjustable) may be necessary to maintain the indoor air temperature at a comfortable level.

Conclusions

From the present investigation, it can be postulated that the thermal models based on laboratory tests at steady state conditions cannot accurately predict the real thermal environment where the climate conditions are transient and where the occupants invariably change their activities especially beyond the comfort zone. For the cases investigated Fanger's equation for thermal comfort over-predicts the neutral temperature by as much as 2K and under-predicts the comfort requirement when air temperature deviates from neutrality. The equation for draught risk fails to predict the response of draught.

To achieve a good indoor climate and air quality, it is necessary to supply fresh air either by opening windows or by installing a suitable vent for the introduction of fresh air. The size of the vent opening should ideally be controllable, either manually or by an odour sensor so that the indoor air will be invigorated, the odour reduced or eliminated and the air freshness enhanced. Also, the heating costs can be reduced by adjusting the heat emission from the radiators using, for example, a thermostatic valve or by a weather compensated heating system.

The air change rates in the room are related to the indoor and outdoor climates by Equations 2 and 4. The turbulence intensity is a function of air change rate as given by Equation 5. Models for evaluating the thermal sensation, air movement and air freshness have also been developed.

Further investigations are underway to evaluate the comfort in this and other offices in order to explore the effects of individuals, climate and room use on the comfort requirements.

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