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COMFORT ASSESSMENT IN A NATURALLY VENTILATED OFFICE

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ABSTRACT

Experiments were carried out to measure the indoor environmental parameters such as air change rate, air velocity, turbulence intensity and air temperature in a naturally ventilated office. 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. Models were developed for assessing the indoor environment which were based on the field measurements.

KEYWORDS

Thermal comfort, air movement, draught, indoor air quality.

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 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 airconditioning systems. The maintenance as well as the design 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 (1982), which are based on the heat balance between the body and environment and subjective testing

in an environmental chamber. 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. Schiller, et al. (1988), for example, 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. Moreover, most laboratory based models for assessing the indoor environment are 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 cold head is preferable but many heating systems produce the opposite effect. Although there are some sophisticated models in which a human body is represented by up to 25 nodes (Thellier, et al. 1991), 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 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. The results of indoor CO_2 measurements have been used to specify minimum ventilation rate requirements. Fanger, et al. (1988a) carried out an extensive survey of indoor air quality for 20 randomly selected office buildings and assembly halls and found that more than 30% of the subjects were dissatisfied with the indoor air quality, even though the average fresh air ventilation rate was 25 l/s per occupant. In order to take into account various sources of pollutants in offices, Awbi (1991) advocates increasing the outdoor supply rates to values much higher than the current recommendations so as to minimise complaints from building-related sickness.

The objective of this work is to evaluate the indoor environment in naturally ventilated offices 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 X 2.3 X 2.6 m (length X width X ceiling height). The effective volume of the room, i.e., the volume excluding the space occupied by obstacles, is approximately 29.3 m^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 radiators in cold seasons; an extra electric heater was 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, turbulence intensity and air temperature were measured continuously at six locations using thermal anemometers. At each location measurements were taken at points 0.1 m (foot/ankle level), 0.6 m (back of a seated person) and 1.1 m (neck/head level of a seated person) above the floor in a vertical line. The plane radiant temperature, temperatures of room surfaces and obstacles and indoor air humidity were measured using an indoor climate analyser. Thermal comfort indices (PMV and PPD) were measured using a comfort meter. A CO_2 gas analyser was used for the measurement of indoor CO_2 concentrations.

The air change 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 and air in the room for a few minutes after injecting the gas. The wind speed and direction were measured with three vane cup anemometers and a wind anemometer mounted on the top of the building (about 5 m above the roof). The outdoor air temperature and humidity were measured using a hand-held humidity meter.

Subjective Assessment

A subjective assessment was carried out for thermal comfort and indoor air quality. 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.

RESULTS AND DISCUSSION

Environmental Parameters

This includes all the measured results for air change rate and

for other parameters concerning the room environment.

Air change rate

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 (Croome and Roberts, 1981), i.e.

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

The infiltration rate due to wind, Q_w, is proportional to wind speed whereas the infiltration rate due to stack, Q_s, 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 correlated as

$$N^2 = 0.0393\ V_w^2 + 0.0154\ \Delta T \qquad (2)$$

where N = air change rate, h^{-1}
V_w = wind speed, m/s
ΔT = indoor-outdoor temperature difference, K.

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 10.0 m/s and the range of the indoor-outdoor temperature difference was between 9.7K and 20.4K.

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

$$N^2 = [a_1 + a_2|\sin(90 - \theta/2)|](V_w A)^2 + b\ \Delta T + c \qquad (3)$$

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 values of the constants a_1, a_2, b and c are shown in Table 1.

Table 1. Opening area and constants for Equation (3)

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

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 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 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 1 for this arrangement was calculated from the mean value of the measured air change rates in order to fit the form of the correlation. The window opening area for the tests performed ranges from 0.036 m^2 to 0.194 m^2. The level of door opening is between slight (0.24 m^2) and half (1.20 m^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 (3) respectively. When all the windows and door were closed the infiltration rates ranged from about 0.44 h^{-1} for a mild and still outdoor climate to 1.94 h^{-1} for a very windy day with a mean of 0.86 h^{-1} or 7 l/s, which is slightly lower than the minimum fresh air requirement to maintain a CO_2 concentration maximum limit of 1000 ppm. 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 1.51 h^{-1} to 5.88 h^{-1} for a window partly open, 3.40 to 10.87 h^{-1} for both the window and door partly open and 2.56 to 4.79 h^{-1} for only the door partly open.

Room environment

The mean **air velocity** in the room was very low with an average of about 0.05 m/s when the windows and door were closed. 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 accordingly. Besides, the air velocity at head level was slightly higher than that at foot 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 0.15 m/s.

The **turbulence intensity** for most of the days was between low and medium with a mean of 22.5% when the windows and door were closed. When the window and/or door were open, the mean of turbulence intensity was increased to 42.0%. The turbulence intensity is related to the air change rate as follows:

$$Tu = 25.76 \, N^{0.42} \qquad (r = 0.68) \qquad (4)$$

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 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. 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 1.1 m and 0.1 m above the floor not to be greater than 3K (ISO, 1984)).

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. 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%.

The following table summarises the distributions of the room environmental data measured with the thermal anemometers.

Table 2. 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

Subjective Evaluation

Out of 46 tests 44 subjective measurements were collected. The rating scales for thermal sensation, air movement, odour intensity and air freshness are shown in Table 3.

Table 3. 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			

Thermal sensation

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 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 under-estimates 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 determining its true 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 $\quad TS = 0.5732\ T - 11.97\ \sqrt[4]{V} - 6.93 \quad (r = 0.66)$ (5a)

foot $\quad TS = 0.5624\ T - 7.53\ \sqrt[4]{V} - 8.28 \quad (r = 0.63)$ (6a)

overall $\quad TS = 0.6146\ T - 12.27\ \sqrt[4]{V} - 7.46 \quad (r = 0.68)$ (7a)

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 $\quad TS = 0.4055\ T - 8.54 \quad (r = 0.52)$ (5b)

foot $\quad TS = 0.5224\ T - 10.84 \quad (r = 0.67)$ (6b)

overall $\quad TS = 0.4815\ T - 10.13 \quad (r = 0.62)$ (7b)

for a window and/or the door open

head $\quad TS = 0.7024\ T - 16.20 \quad (r = 0.70)$ (5c)

foot $\quad TS = 0.6939\ T - 15.26 \quad (r = 0.62)$ (6c)

overall $\quad TS = 0.8371\ T - 18.95 \quad (r = 0.72)$ (7c)

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

In Figure 4 the occupant's thermal sensation responses are presented as a function of mean air temperature, using a mean air velocity of 0.06 m/s for Equations (5a), (6a) and (7a). The PMV curve predicted from Fanger's equation is also presented for comparison (assuming a metabolic rate of 1.2 met and a clo value of 0.8). From the above equations or the corresponding curves in Figure 4 the neutral temperatures (T_n), i.e. T for TS = 0, can be obtained. The neutral temperature predicted from Fanger's equation is 22.8°C for air velocities between 0.05 and 0.075 m/s. The calculated neutral temperatures from the above equations together with the difference in neutral temperature, ΔT_n, between Fanger's equation and Equations (5), (6) and (7) are shown in Table 4.

Table 4. Neutral temperatures from the field measurements compared with Fanger's value of 22.8°C

Equation	(5a) Head	(6a) Foot	(7a) Overall	(5b) Head	(6b) Foot	(7b) Overall	(5c) Head	(6c) Foot	(7c) 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 can be seen from Table 4 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 confirm the findings by Schiller, et al. (1988). A more obvious and important point is that from the present investigation the correlated curves in Figure 4, 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 (1979) 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.

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 responses 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 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

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:

$$AM = 0.1462\ T - 20.31\ V - 0.0048\ Tu - 1.71 \quad (r = 0.57) \qquad (8)$$

at head level;

$$AM = 0.2037\ T - 6.65\ V - 0.0081\ Tu - 3.64 \quad (r = 0.44) \qquad (9)$$

at foot level;

$$AM = 0.1455\ T - 18.99\ V - 0.0069\ Tu - 1.69 \quad (r = 0.56) \qquad (10)$$

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.

Equations (8) and (10) 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. Moreover, these two equations indicate that an increase in mean velocity of about 0.05 m/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 0.05 m/s to 0.10 m/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. (1988b), based on the laboratory testing, derived the following equation for the calculation of the percentage of dissatisfied due to draught:

$$PD = (3.143 + 0.3696\ V\ Tu)(34 - T)(V - 0.05)^{0.6223} \qquad (11)$$

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 0.10 m/s and temperature around 20.0°C. Again, the laboratory model fails to fully predict the comfort in practice because it under-estimates the effect of air velocity. Equation (11) indicates that the draught risk is small at a velocity close to 0.05 m/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 0.3 m/s (Clark and Toy, 1975). Using the air temperature and velocity near the body, Equation (11) 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.

Odour intensity

Odour was detectable in most cases when the windows and door were closed and was rated as being slight. The measurement of CO_2 levels indicated that its concentration was normally well above the criterion of 1000 ppm with occupancy at low air change rates. Even when the air change rate was higher than 10 l/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 500 ppm indoors compared to 300 ppm 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 - 1000 ppm 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 in other cases where the CO_2 level was higher than 1000 ppm 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

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 (1981). 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 (1948) who pointed out that a cool room tended to feel fresh and an overheated one stuffy. The impressions of stuffiness at comfortable temperature 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 slightly 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:

$$AF = 0.0863\ T - 19.37\ V - 0.0130\ Tu \qquad (r = 0.66) \qquad (12)$$

Equation (12), 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 0.05 m/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.

CONCLUSIONS

From the present investigation, it can be postulated that the thermal models based on laboratory tests at steady state conditions can not 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 overpredicts 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 to 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.

The air change rates in the room are related to the indoor and outdoor climates by Equations (2) and (3). Models for evaluating the thermal sensation, air movement and air freshness have also been developed.

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GLOSSARY

Air change rate — the rate at which air inside a room is exchanged with air outside the room due to the continual transfer of air across the room envelope.

Clo value — the total thermal resistance from the skin to the outer surface of the clothed body.

Draught — the unwanted local cooling of the human body caused by air movement.

Turbulence intensity — the standard deviation divided by the mean velocity of air in turbulent flow.

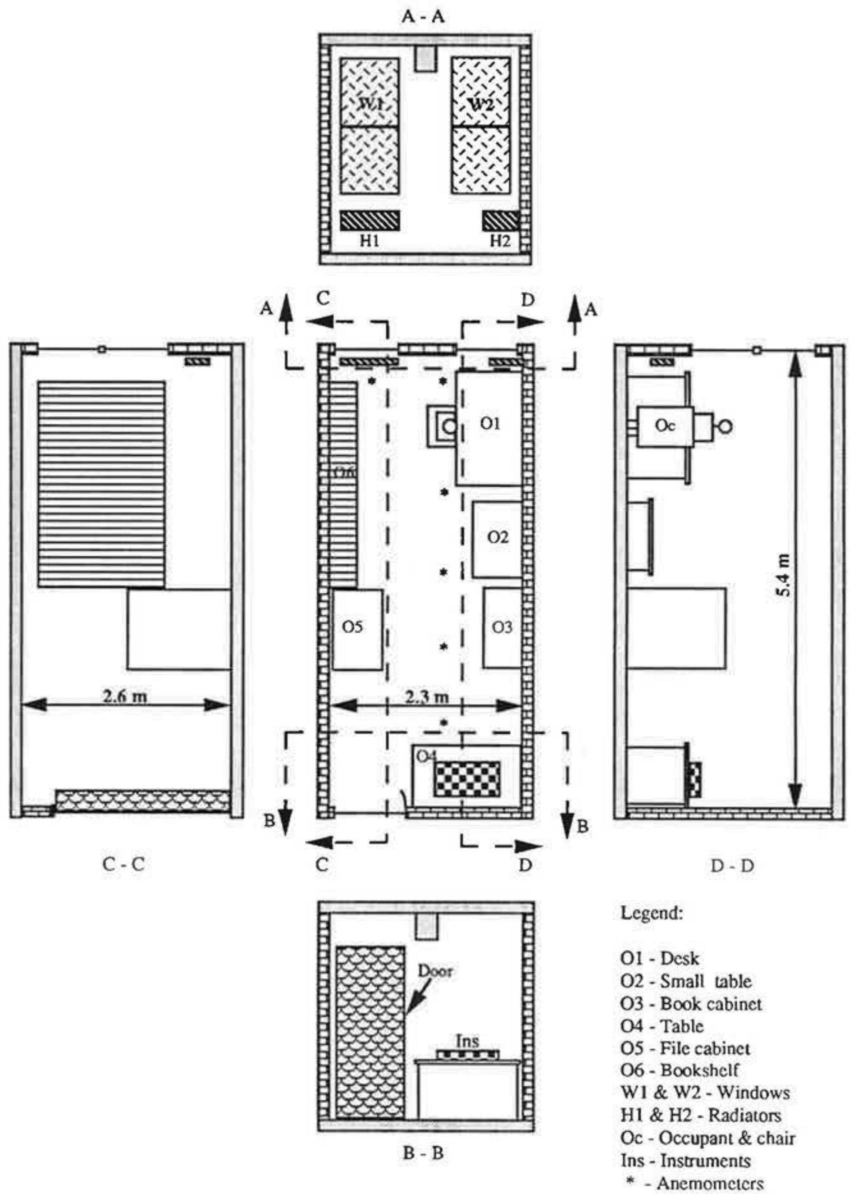


Fig. 1 Schematic of the test room

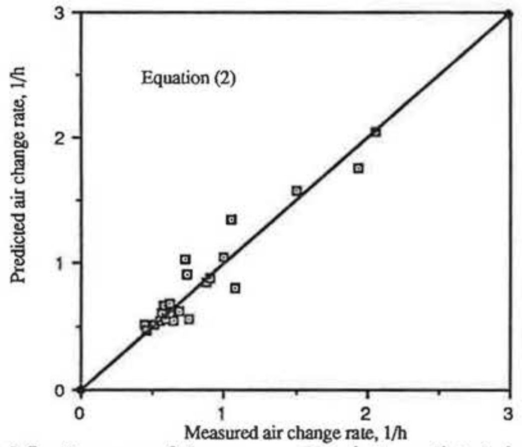


Fig. 2 Scattergram of the measured against predicted air change rate with windows and door closed

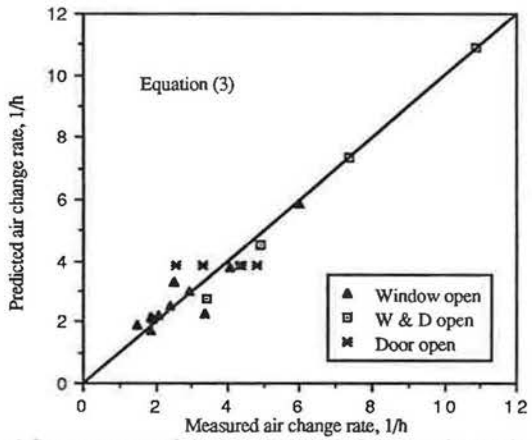
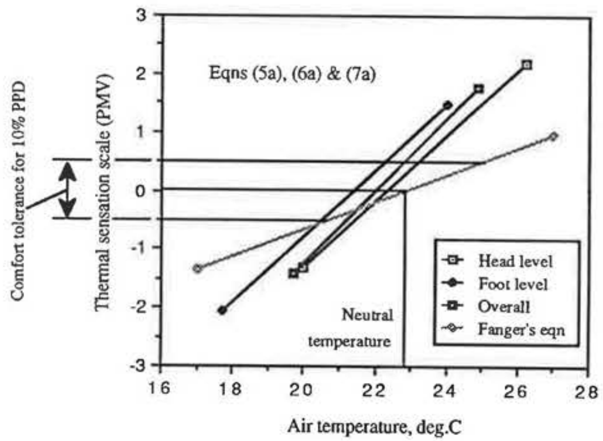
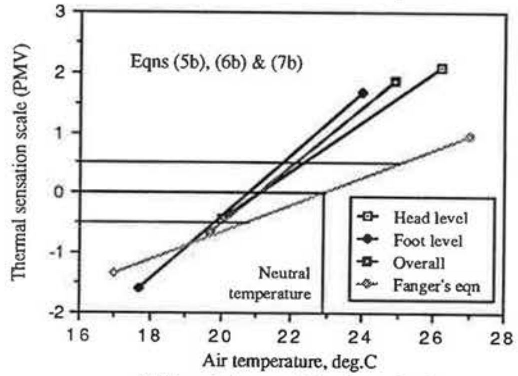


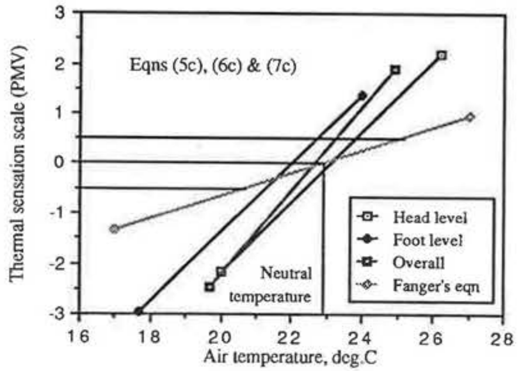
Fig. 3 Scattergram of the measured against predicted air change rate with window and/or door partly open



(a) for all the window & door arrangements



(b) for windows and the door closed



(c) for a window and/or the door open

Fig. 4 Effect of air temperature on thermal sensation responses

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