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Field Evaluation of the Indoor Environment of Naturally Ventilated Offices.

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SYNOPSIS

Experiments were carried out in four naturally ventilated offices to measure the indoor environmental parameters such as air velocity, turbulence intensity and air temperature at three vertical levels. Air change rates for various indoor and outdoor climates were 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 offices. The effect of opening windows and doors on the indoor comfort conditions was also investigated.

Models were developed for assessing the indoor environment based on the field measurements. It was found that in real situations the occupants were more sensitive to the deviation of air temperature from neutrality than predicted using Fanger's comfort model. The indoor environment in the offices was found to be unsatisfactory and recommendations are given for its improvement.

1. INTRODUCTION

Thermal comfort is an important factor that influences occupants' satisfaction with the room environment. Fanger[1] developed models for the prediction of indoor thermal comfort based on laboratory testing. However, a number of field studies have shown that these models could not accurately predict the occupants' thermal responses under working surroundings. For example, Schiller, et al.[2] found that optimum satisfaction with the thermal environment in office buildings was achieved at a lower temperature than that found under laboratory conditions. Moreover, these laboratory based models are derived from measured data which give an overall state of room environment but not the sensitivity of different parts of the body to the surroundings. A more reasonable model for comfort should be able to reflect these differences.

Air quality in offices has been a major concern in recent years. Odour intensity is one of the indicators of indoor air quality and is often associated with the level of carbon dioxide. The results of indoor CO_2 measurements have been used to specify minimum ventilation rate requirements. However, Fanger, et al.[3] found that more than 30% of the subjects were dissatisfied with the indoor air quality in randomly selected office buildings and assembly halls even though the average ventilation rate was up to 25 l/s per occupant, which is far higher than the recommended value of 7-8 l/s per person referred to in the CIBSE Guide[4] and based on the maximum allowable CO_2 level of about 1000 ppm. This could have been attributed to the presence of other sources of pollution indoors as well as poor air distribution to the occupied zone.

The objective of the present work is to evaluate the indoor environment in naturally ventilated offices using detailed field measurements of the environmental parameters and thence to develop models for assessing indoor thermal comfort and air quality based on the field measurements.

2. METHOD

This investigation has been carried out by means of physical measurements combined with a subjective assessment of the indoor environment in four naturally ventilated office rooms (denoted as room A, room B, room C and room D). The offices are situated in the FURS building at the University of Reading. Rooms A and B are built of one concrete external wall and three concrete brick walls connected to other rooms, situated in the north wing of the building. They are both connected to the north corridor via hinged wooden doors. There are two small weatherstripped double-hung aluminium frame windows in the north face of room A and one large window in the north face of room B. Room C is located between the two corridors which connect the south and north wings. The walls separating the room and the corridors are glazed while the other walls are made of concrete bricks. There is a small axial fan in the north face near the ceiling for supplying air into the room. Room D has a similar structure to room A but is situated in the south wing and connected to the south corridor. All the offices are heated by hot water radiators in cold seasons. During hot days a portable propeller fan was used in some of the tests. The investigation lasted for eight months in the year 1991/92. In terms of seasons, tests were conducted in winter in room A, early spring in room B, late spring in room C and early summer in room D.

2.1 Physical measurements

During an experimental test the air velocity, turbulence intensity and air temperature were measured using thermal anemometers (DANTEC Multi-channel Flow Analyser type 54N10). Measurements were taken at points 0.1 m (foot/ankle level), 0.6 m (centre of gravity of a seated person) and 1.1 m (neck/head level of a seated person) above the floor. The plane radiant temperature 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 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 speed was measured with three vane cup anemometers and the wind direction with 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 copper-constantan thermocouple (radiation shielded) and a hand-held humidity meter respectively.

2.2 Subjective assessment

A subjective assessment was made simultaneously with the physical measurements. The assessment of the thermal environment was based on the occupants' vote on the thermal sensation and air movement in the offices under various outdoor and indoor conditions and different arrangements of window and door openings. This assessment was 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. These rating scales are given in Table 1.

Table 1. 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			

3. RESULTS AND DISCUSSION

A summary of the results for physical measurements of the environment in the four rooms is shown in Table 2. These results are discussed and compared with those obtained from subjective evaluation.

3.1 Thermal sensation

The mean thermal sensation was found to be on the warm side of the neutral point defined in Table 1. However, the measured PMV values, which were obtained using Fanger's comfort equation, were close to the neutral point for most of the test conditions. This suggests that Fanger's equation under-estimates the thermal impressions and is less sensitive to changes in the environmental and personal parameters. This may be

Table 2. Physical properties of room environment

Item / Room No.	A	B	C	D	ABCD*
Dimension (m)					
Length	5.4	11.6	4.2	4.4	
Width	2.3	2.9	3.5	2.3	
Height	2.6	3.4	2.6	2.6	
Effective volume+ (m^3)	29.3	108.2	37.5	25.0	
Normal occupants	1	3	2	1	
Average air change rate (h^{-1})	0.86	0.86	7.60	3.03	
Average air supply rate (l/s per person)	7.0	8.6	36.9	21.0	
Mean air velocity (m/s)					
Head level	0.059	0.071	0.098	0.063	0.072
Foot level	0.064	0.100	0.111	0.086	0.081
Overall	0.060	0.082	0.099	0.067	0.076
Turbulence intensity (%)					
Head level	39.4	59.2	43.8	38.6	43.8
Foot level	28.7	44.4	34.0	33.0	34.0
Overall	34.7	54.3	41.2	37.1	40.4
Mean air temperature (°C)					
Head level	23.1	23.8	25.7	27.1	24.8
Foot level	21.4	21.7	24.5	25.0	23.1
Overall	22.4	22.9	25.1	26.2	24.0
Difference between air temperature and radiant temperature (K)	0.6	0.7	-0.7	0.6	0.4
Relative humidity (%)	45.8	45.7	42.9	47.6	45.5
Calculated neutral temperature (°C)					
Head level	22.4	22.4	23.2	22.8	22.2
Foot level	21.4	20.4	21.1	22.1	21.0
Overall	22.0	21.7	22.5	22.7	21.8
Neutral temperature predicted from Fanger's equation (°C)	22.8	22.8	22.3	22.9	22.7
Difference in neutral temperature between measured and predicted (K)					
Head level	0.4	0.4	-0.9	0.1	0.5
Foot level	1.4	2.4	1.2	0.8	1.7
Overall	0.8	1.1	-0.2	0.2	0.9

Notes: * average of the data for rooms A, B, C and D;
+ excluding the space occupied by obstacles.

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 approximation of the metabolic rates of the occupants (1.2 met). The third reason is the sensitivity of PMV to clo values (thermal resistance of clothing). In a laboratory test the clo values are consistent whereas in field tests the clothing levels vary with occupants and time.

From the data for the four rooms it was found that the thermal sensation is linearly related to the air temperature. The regression equations for the thermal sensation judgement at head level, foot level and overall against mean air temperature (T, °C) (involving 133 data points) are as follows:

head	TS = 0.3915 T - 8.66	(r = 0.70)	(1)
foot	TS = 0.4655 T - 9.78	(r = 0.72)	(2)
overall	TS = 0.4586 T - 10.01	(r = 0.73)	(3)

where r is the correlation coefficient. The correlations have confidence levels of 99.5%.

Figure 1 shows the relationship between the occupant's thermal sensation response and mean air temperature. The PMV line 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 and using the average values of the measured air velocity and radiant temperature for the four rooms). From such equations or the corresponding plots in Figure 1 the neutral temperatures T_n corresponding to TS = 0 can be obtained. The neutral temperature predicted using Fanger's equation is the air temperature corresponding to PMV = 0. The calculated neutral temperatures from the correlated equations and from Fanger's equation together with the difference in neutral temperature between them are shown in Table 2.

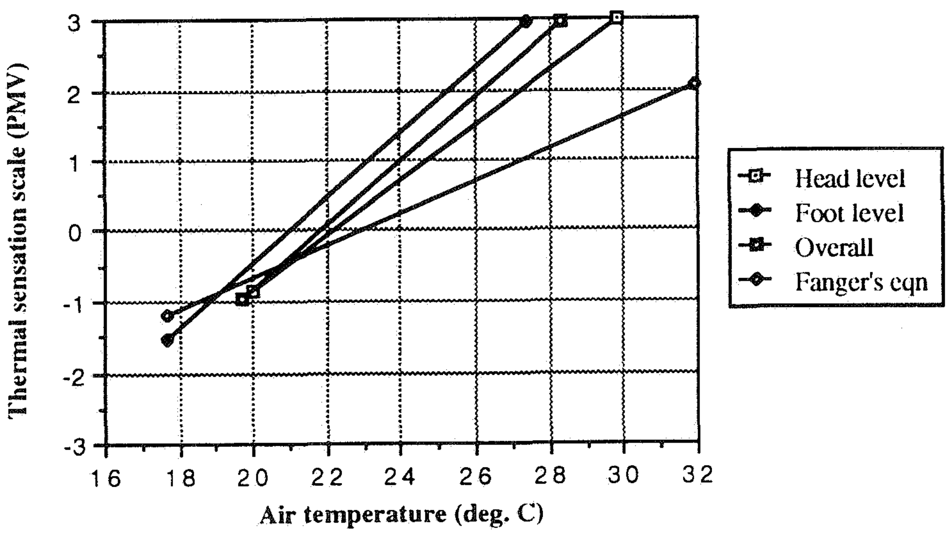

Fig. 1 Effect of air temperature on thermal sensation responses

It can be seen from Table 2 that Fanger's equation generally overpredicts the neutrality, which confirms the findings by Schiller, et al.[2] and Brager[5]. They found that the predicted neutral temperature was on average 2.4K higher than that measured for 304 workers in 10 buildings. Kahkonen[6] also found that workers in offices estimated the thermal environment warmer than that calculated using Fanger's equation. Another important feature from the present investigation is that the correlated curves in Figure 1 are steeper than that given by Fanger's equation, suggesting the occupants are more sensitive to changes in air temperature. This fact was also observed by Fishman and Pimbert[7] whose field study showed that the gradient of the curve from the observations deviated from Fanger's equation particularly at temperatures above 24°C. In addition they found that Fanger's comfort equation over-predicted the neutral temperature by 0.6K compared with that from the field survey. This was attributed to the incorrect estimation of the subjects clothing.

Fanger[1] defined the central three categories of the thermal sensation scale as an indication of an acceptable state for thermal comfort whereas the votes outside these central categories as dissatisfaction with the thermal state. According to this definition, the results suggest that one quarter to one half of the responses were dissatisfied with the thermal environment. Most of the dissatisfaction that occurred in rooms A and B when the windows and door were closed in cold seasons was caused by overheating, which could be avoided by controlling the heat output from the emitters if a thermostat was available or by window opening. For room C however these measures are not sufficient because the heater was turned off in the test period. One way to decrease the indoor temperature is to introduce air directly from the outside of the building rather than from the corridor (as it was the case during the tests) using the existing ventilating fan. Due to its location a comfortable thermal environment for room D is difficult to achieve in hot sunny days during the summer unless it is air conditioned.

3.2 Air movement

The overall impression of the air movement in the rooms was on the side of being stagnant. Although the measured air velocity and turbulence intensity in rooms C and D were generally higher than those in room A, the proportion of votes on being stagnant or very stagnant was higher in these two rooms. This may be attributed to the higher air temperature in the rooms. For room A when a window and/or the door were partly opened, the impression of air movement shifted to being slightly draughty[8]. The main cause of the draught was attributed to the low temperature as the air velocity and turbulence intensity were not high.

The correlations between the ratings for air movement (AM) and the indoor environmental parameters are as follows:

head $AM = 0.1258\ T - 4.28\ V - 2.35$ $(r = 0.42)$ (4)

foot $AM = 0.1579\ T - 3.13$ $(r = 0.42)$ (5)

Overall $AM = 0.1401\ T - 4.65\ V - 0.0060\ Tu - 2.31$ $(r = 0.45)$ (6)

where T is the air temperature (°C), V is the air velocity (m/s) and Tu is the turbulence intensity (%).

Defining a "comfortable" temperature for air movement as the air temperature corresponding to an acceptable air movement, such a temperature can be derived from Equations (4) to (6) for specified values of air velocity and turbulence intensity. Using the average values of air velocity and turbulence intensity for the four rooms, the calculated comfortable temperatures are 21.1°C, 19.8°C and 20.7°C for the head level, foot level and overall judgement respectively, which are about 1K lower than the corresponding neutral temperatures. It seems that the preferred indoor temperature for air movement is lower than that for thermal sensation. Therefore a compromise between the requirements for warmth and air movement may have to be made sometimes to achieve an acceptable thermal condition.

3.3 Odour intensity

In room A odour was detectable in most cases. The measurement of CO_2 levels during occupancy indicated that its concentration was normally well above the criterion of 1000 ppm at low air change rates when the windows and door were closed[8]. 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.

Although the air flow rate in room B was higher than in room A and the CO_2 level was usually below 1000 ppm, there was a higher proportion of complaints on the odour intensity than those experienced in other rooms. The following two causes may be attributed to the complaints. One is the occasional smoking by one of the occupants and the other is the old furnishings in the room. In contrast, a large proportion of votes in room C showed that odour was not detectable and there was no evidence of strong odour. This is consistent with the measured low CO_2 concentrations in the room because of the provision of the ventilating fan which maintained the indoor CO_2 at a similar level to that in the corridor of around 700 ppm (during the Easter vacation period). In room D there was an even distribution of odour intensity between undetectable and moderate except for a small fraction of votes for strong odour. The CO_2 level in this room with occupancy was normally above 1000 ppm and odour was detectable when the windows were shut and the odour level decreased when a window was partly open.

In this investigation, no satisfactory correlation between odour intensity, CO_2 level and air change rate could be established. 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 have been more significant than the CO_2 emission from the occupants. Also, the judgement could have been affected by a fatigue of the olfactory sense of the occupants.

3.4 Air freshness

In rooms A, B and D the rating of air freshness was in general slightly stuffy and occasionally the air was rated as fresh when the air temperature was lower than the neutral temperature. In room C however there was no impression of very fresh air due to the predominantly high air temperature.

Air freshness may be related to the air temperature, velocity and turbulence intensity in the following form:

$$AF = 0.0474\ T - 3.02\ V - 0.0107\ Tu \qquad (r = 0.48) \qquad (7)$$

Thus, air freshness increases when the air temperature decreases; or when the air velocity or turbulence intensity increases.

5 CONCLUSIONS

Models for evaluating the thermal sensation, air movement and air freshness have been developed. These parameters are dependent on the air temperature, velocity and turbulence intensity under normal office conditions. When the indoor air temperature is substantially higher than that for neutrality, temperature is the predominant factor that decides the occupants' response to thermal comfort and air freshness.

From the present investigation, it can be postulated that thermal models based on laboratory tests at steady state conditions can not accurately predict the real thermal environment where the climatic conditions are transient and where the occupants invariably change their activities or clothing especially beyond the comfort zone. For the cases investigated Fanger's equation for thermal comfort generally overpredicts the neutral temperature and under-predicts the comfort requirement when air temperature deviates from neutrality.

To achieve a good indoor climate and air quality, fresh air should be introduced into rooms either by opening windows or by installing a suitable vent. 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 in cold seasons can be reduced by adjusting the heat emission from radiators using, for example, a thermostatic valve or by a weather compensated room heating system.

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