THERMAL COMFORT MODELS BASED ON FIELD MEASUREMENTS

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ABSTRACT

Experiments were carried out in five naturally ventilated offices to measure the indoor environmental parameters such as air velocity, turbulence intensity, and air temperature. Air change rates for various indoor and outdoor climates were determined. The concentration of carbon dioxide in the rooms was monitored. Subjective assessment was made to evaluate the thermal comfort and air quality in the offices. The data were used to develop models that can be used to assess the indoor environment of naturally ventilated offices. Results from the present investigation show that the thermal sensation in work environments differs from that evaluated under laboratory conditions. It is also shown that the energy consumption for space heating can be reduced by lowering room temperature. Assessment of potential energy savings for the UK climate is given in paper.

INTRODUCTION

Thermal comfort is an important factor that influences occupants' satisfaction with the room environment. The relationship between thermal comfort and environmental parameters has long been subjected to investigation. Fanger (1982) has developed a set of the most comprehensive models to date for the prediction of indoor thermal comfort, PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) based on laboratory testing. His results have been adopted in an international standard (ISO 1984). However, a number of field studies showed that these models could not accurately predict the occupants' thermal responses in work surroundings, particularly in naturally ventilated buildings (Humphreys 1976; de Dear and Auliciems 1985). Occupant's adaptation was considered to be an important part of the discrepancy between laboratory and field measurements. McIntyre (1980) considered that judgments of sensation might be dependent in some degree on context and expectation and that comfort studies should be conducted in the real world as well as in the laboratory. McIntyre (1978) suggested that the discrepancy between laboratory and field studies could be investigated by asking more detailed questions about the thermal state of the respondent, including sensation in different parts of the body. The laboratory-based models are derived from measured data that give an overall state of the room environment (PMV for a whole body) but not the sensitivity of different parts of the body to the surroundings. A more accurate model for comfort should be able to reflect these differences.

Air quality in offices has been a major concern in recent years, particularly due to increasing numbers of reports of sick building syndrome. Odor intensity is one of the indicators of indoor air quality and is often associated with the level of carbon dioxide (Yaglou et al. 1936). The results of indoor CO_2 measurements are used to specify minimum fresh air requirements (CIBSE 1986; ASHRAE 1989). However, poor air distribution in a space can result in occupant dissatisfaction with the indoor air quality even if the ventilation rate is higher than the minimum requirement.

To achieve comfort in buildings currently requires almost 40% of the world's nonrenewable energy. Besides increasing energy expenditure, fossil fuel burning substantially contributes to the accumulation of some undesirable gases in the atmosphere, such as CO_2 and the CFCs used in refrigeration systems. A comfortable indoor environment with minimum energy use can be achieved through careful design and management of the building and the associated environmental systems as well as making use of improved building technology, such as good thermal insulation, reduced air infiltration, employment of heat recovery systems, and use of renewable energy and of building energy control systems. Energy consumption in offices may also be reduced by lowering indoor air temperature, hence reducing heating costs. This is because many offices are overheated due to lack of individual control of heat supply and because optimum satisfaction with the thermal environment in office buildings can be achieved at a lower temperature than that obtained under laboratory conditions (Schiller et al. 1988; Brager 1992).

The objectives of this work are twofold. One is to develop models for assessing indoor thermal comfort and air quality based on field measurements. The other is to

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investigate the potential for saving energy by exploiting some measures to reduce the requirement for space heating use.

METHOD

This investigation has been carried out by means of physical measurements combined with a subjective assessment of the indoor environment in five naturally ventilated office rooms (denoted as rooms A, B, C, D, and E) at a British building. Rooms A, B, C, and D are staff offices and room E accommodates several workstation computers. Rooms A and B have one concrete external wall and three concrete brick walls connected to other rooms situated in the north wing of the building. These two rooms are each connected to the north corridor via hinged wooden doors. There are two small windows and one large weatherstripped double-hung aluminium frame window in the north face of room A and room B, respectively. Room C is located between the south and north 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 and room E have structures similar to room A and room B, respectively, but both are situated in the south wing and connected to the south corridor. Rooms A, C, and D are heated by hot water radiators in cold seasons. In room B, there is a full-width convector under the window in addition to two radiators for heating. Room E is heated by a convector of the same type as that for room B under the window in the south wall. During hot days, a rotating fan was used in some of the tests. The investigation lasted for 14 months. Tests were conducted in winter (1991) in room A, early spring (1992) in room B, late spring in room C, summer in room D, and in winter (1992) in room E.

Physical Measurements

During a test, the indoor air velocity, turbulence intensity, and air temperature were measured continuously using thermal anemometers. Measurements were taken at points 0.1 m (foot/ankle level), 0.6 m (center 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 analyzer. Thermal comfort indices (PMV and PPD) were measured using a comfort meter. A CO_2 gas analyzer was used for the measurement of indoor CO_2 concentrations.

The air change rate was determined using the concentration decay method with an infrared gas analyzer. A portable fan was employed to ensure a good mixing of tracer gas (isobutane) and air in the rooms for a few minutes after injecting the gas. The indoor environment is linked to the outdoor climate through air exchange as well as heat exchange. Measurements were, therefore, made of the outdoor conditions such as wind velocity, air temperature, and humidity. 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. Appendix A describes the measured variables other than thermal anemometer readings during a test.

Subjective Assessment

A subjective assessment was undertaken simultaneously with the physical measurements. Occupants of the offices were asked to fill out a questionnaire concerning their environmental impressions as well as clothing levels. A sample questionnaire for subjective assessment is shown in Appendix B. Each questionnaire reflected the occupant's impressions of the indoor environment for a period of over one hour. In order to investigate the variation of comfort rating with environmental parameters under working conditions, repeated measurements were taken for a group of subjects on different days but not in the same day. McIntyre (1978) has shown that the between and within subject variability is similar and recommended that a continuous scale be used for repeated measurements. The assessment of the thermal environment was based on the occupant's 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 judgments at head and foot levels as well as for overall comfort. The indoor air quality was assessed according to the impressions of odor 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, odor intensity, and air freshness. Table 1 shows the rating scales for these thermal environment and air quality indices.

EXPERIMENTAL RESULTS AND DISCUSSION

A summary of the results of physical measurements of room environment is presented in Table 2. These measured results are discussed together with those from the subjective evaluation.

Room Environment

The physical data for the room environment, except for the air change rate, were obtained for every test. Figures 1 through 3 show the distributions of mean air velocity, turbulence intensity, and mean air temperature at head level, foot level, and overall (mean of the values for three heights measured), respectively.

The air velocity in these rooms was usually below 33.5 fpm (0.17 m/s) when the windows and doors were closed and fans were not in operation. Velocities above 33.5 fpm

TABLE 1
Rating Scales for Thermal Sensation (TS), Air Movement (AM), Odor 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			

(0.17 m/s) resulted either from the provision of an additional fan used on warm days in room D or from opening windows in rooms C, D, and E. It is seen from Figure 1 that the air velocity at foot level was usually higher than that at head level, especially in rooms B and D, which have a ceiling level higher than that of the other three rooms.

The turbulence intensity was between low and moderate for room A but between moderate and high in the other four rooms (Figure 2). Unlike the results of Melikov et al. (1988), which indicate that the magnitude of turbulence intensity increases with a decrease in the mean air velocity, the effect of air velocity on turbulence intensity is not significant.

The indoor air temperature changed from day to day during the course of measurement (Figure 3) due to the fluctuations of outdoor temperature, air change rate, and heat loss or gain from the rooms and due to opening the windows or doors. In some tests, overheating was observed during mild outdoor weather. Temperatures much higher than 78.8°F (26.0°C) were due to the solar heat gain from the partly opened south window of room D in the summer. It can also be seen that the air temperature at head level is higher than that at foot level with a mean vertical temperature difference of 3.1°F (1.7 K). The relative humidity in the room throughout the test period was normally within the comfort limits, ranging from 40% to 55%.

The measured plane radiant temperature and thereby the calculated mean radiant temperature were generally lower than the mean air temperature for all rooms, except for room C where there is no external wall exposed to cold ambient. The average difference between the mean air temperature and mean radiant temperature for all the tests was within 1.8°F (1.0 K).

The air change rate was determined for most of the tests in rooms A, B, D, and E. However, only one test was carried out for room C because the ventilating fan was always on during the occupancy and the air change rate was considered to be constant. The air change rate for room A was correlated as functions of the wind speed and direction, indoor-outdoor temperature difference, and opening area of window and/or door (Croome et al. 1992).

Subjective Evaluation

Figures 4 thorugh 6 present the distributions of votes over space and time on thermal sensation, air movement, odor intensity, and air freshness.

Thermal Sensation As shown in Figure 4, the mean thermal sensation was on the warm side of the neutral point. However, the measured PMV values, which were obtained from Fanger's comfort equation (Fanger 1982) for the corresponding tests, were close to the neutral point for most of the test conditions. This suggests that Fanger's equation underestimates the thermal impressions and undervalues the deviations of the impressions from neutrality. This is due to three reasons. One is the assumption of steady-state laboratory conditions used in the derivation of Fanger's equation. Second is the inaccurate estimation of the metabolic rates of the occupants. The metabolic rate was taken as 1.2 met because of the difficulty in its determination under working conditions. 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. In this field study, the clo values were estimated from the occupants' clothing ensembles.

The thermal sensation was found to be dependent on the air temperature and velocity in room A. The effect of air velocity was, however, insignificant for other rooms probably because of insufficient data collected for each subject or too high an indoor air temperature to be compensated for by a small increment of air velocity. The regression equation for the thermal sensation (TS) at head level, foot level, and overall for the rooms against mean air temperature and, for room A, velocity can be expressed as follows:

$$TS = a\,T - b\,V - c \tag{1}$$

where

T = mean air temperature, °F (°C);

TABLE 2

Physical and Thermal Properties of Room Environemnt (I-P Units)

[redacted]

Item / Room No.	A	B	C	D	E	ABCDE*
Dimension (ft)						
Length	17.7	38.0	13.8	14.4	24.9	
Width	7.5	9.5	11.5	7.5	7.9	
Height	8.5	11.2	8.5	8.5	11.2	
Effective volume+ (ft^3)	1034	3818	1323	882	2188	
Normal occupants	1	3	2	1	3$	
Average air change rate (h^{-1})	0.86	0.86	7.60	3.03	3.81	
Average air supply rate (cfm per person)	14.8	18.2	78.2	44.5	46.4	
Number of observations	44	26	33	30	30	163
Mean air velocity (fpm)						
Head level	11.6	14.0	19.3	12.4	13.0	14.0
Foot level	12.6	19.7	21.8	16.9	25.6	18.7
Overall	11.8	16.1	19.5	13.2	19.3	15.7
Turbulence intensity (%)						
Head level	39.4	59.2	43.8	38.6	47.8	44.5
Foot level	28.7	44.4	34.0	33.0	28.1	32.9
Overall	34.7	54.3	41.2	37.1	39.6	40.3
Mean air temperature (°F)						
Head level	73.6	74.8	78.3	80.8	73.6	76.1
Foot level	70.5	71.1	76.1	77.0	71.1	73.0
Overall	72.3	73.2	77.2	79.2	72.3	74.7
Difference between air temperature and radiant temperature (°F)	1.1	1.3	-1.3	1.1	1.3	0.9
Relative humidity (%)	45.8	45.7	42.9	47.6	45.5	45.5
Clothing level	0.8	0.8	0.8	0.8	1.0	0.83
Measured neutral temperature (°F)						
Head level	72.1	72.3	73.7	73.0	70.0	71.0
Foot level	70.5	68.7	70.0	71.8	69.8	69.8
Overall	71.5	71.1	72.5	72.9	70.4	71.0
Predicted neutral temperature from Fanger's equation (°F)#	73.0	73.0	72.1	73.2	70.5	72.6
Difference in neutral temperature between predicted and measured (°F)						
Head level	0.9	0.7	-1.6	0.2	0.5	1.6
Foot level	2.5	4.3	2.2	1.4	0.7	2.9
Overall	1.4	2.0	-0.4	0.4	0.1	1.6

Notes: * average of the data for rooms A, B, C, D and E;
+ the volume excluding the space occupied by obstacles;
$ the occupants are not the normal office users;
# based on the occupants' metabolic rate 1.2 met.

TABLE 2 (cont.)

(SI Units)

Item / Room No.	A	B	C	D	E	ABCDE*
Dimension (m)						
Length	5.4	11.6	4.2	4.4	7.6	
Width	2.3	2.9	3.5	2.3	2.4	
Height	2.6	3.4	2.6	2.6	3.4	
Effective volume+ (m^3)	29.3	108.2	37.5	25.0	62.0	
Normal occupants	1	3	2	1	3$	
Average air change rate (h^{-1})	0.86	0.86	7.60	3.03	3.81	
Average air supply rate (L/s per person)	7.0	8.6	36.9	21.0	21.9	
Number of observations	44	26	33	30	30	163
Mean air velocity (m/s)						
Head level	0.059	0.071	0.098	0.063	0.066	0.071
Foot level	0.064	0.100	0.111	0.086	0.130	0.095
Overall	0.060	0.082	0.099	0.067	0.098	0.080
Turbulence intensity (%)						
Head level	39.4	59.2	43.8	38.6	47.8	44.5
Foot level	28.7	44.4	34.0	33.0	28.1	32.9
Overall	34.7	54.3	41.2	37.1	39.6	40.3
Mean air temperature (°C)						
Head level	23.1	23.8	25.7	27.1	23.1	24.5
Foot level	21.4	21.7	24.5	25.0	21.7	22.8
Overall	22.4	22.9	25.1	26.2	22.4	23.7
Difference between air temperature and radiant temperature (K)	0.6	0.7	-0.7	0.6	0.7	0.5
Relative humidity (%)	45.8	45.7	42.9	47.6	45.5	45.5
Clothing level	0.8	0.8	0.8	0.8	1.0	0.83
Measured neutral temperature (°C)						
Head level	22.3	22.4	23.2	22.8	21.1	21.7
Foot level	21.4	20.4	21.1	22.1	21.0	21.0
Overall	21.9	21.7	22.5	22.7	21.3	21.7
Predicted neutral temperature from Fanger's equation (°C)#	22.8	22.8	22.3	22.9	21.4	22.6
Difference in neutral temperature between predicted and measured (K)						
Head level	0.5	0.4	-0.9	0.1	0.3	0.9
Foot level	1.4	2.4	1.2	0.8	0.4	1.6
Overall	0.9	1.1	-0.2	0.2	0.1	0.9

Notes: * average of the data for rooms A, B, C, D and E;
+ the volume excluding the space occupied by obstacles;
$ the occupants are not the normal office users;
# based on the occupants' metabolic rate 1.2 met.

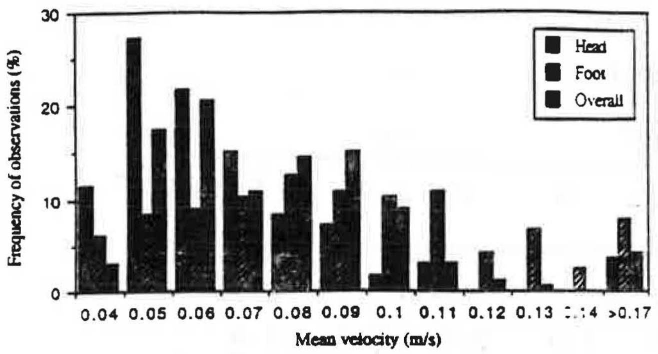

Figure 1 *Frequency distribution of mean air velocity.*

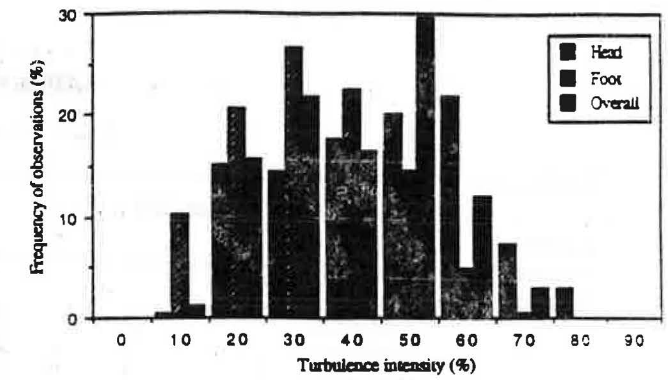

Figure 2 *Frequency distribution of turbulence intensity.*

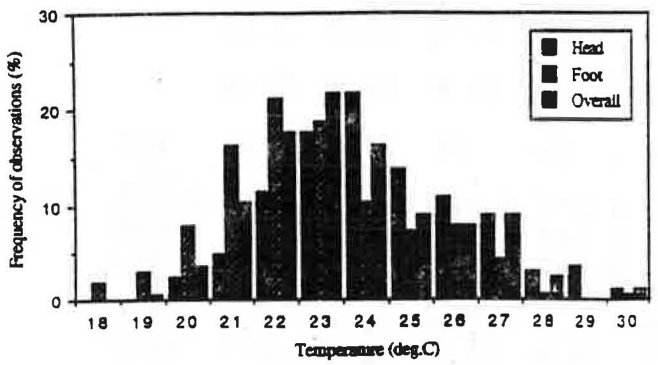

Figure 3 *Frequency distribution of mean air temperature.*

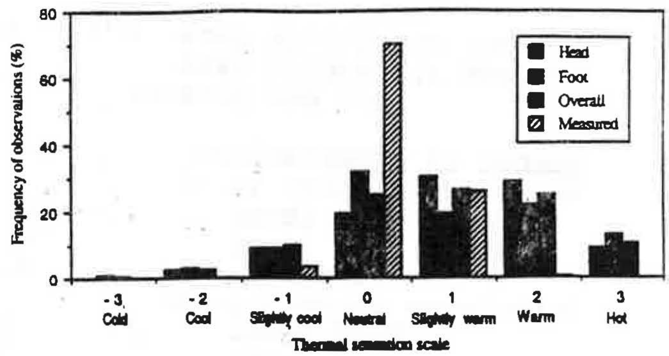

Figure 4 *Frequency distribution of thermal sensation votes.*

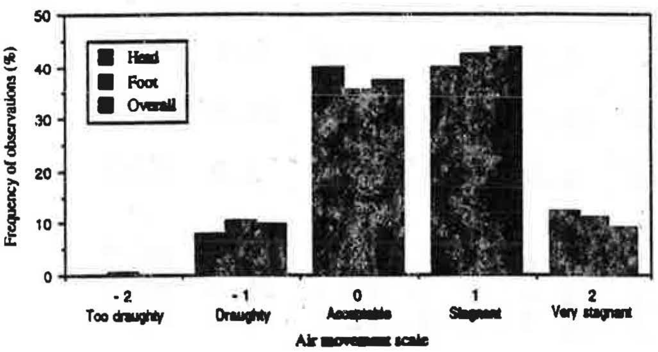

Figure 5 *Frequency distribution of air movement votes.*

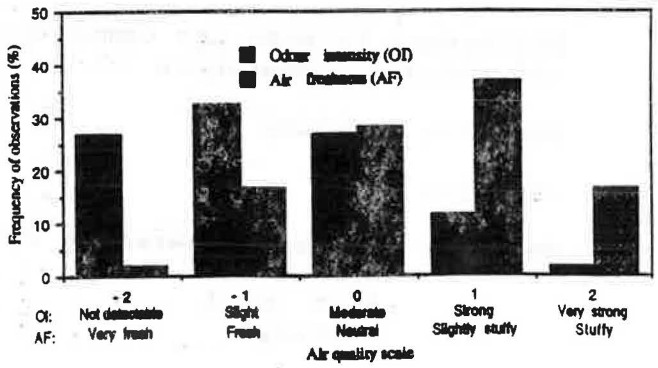

Figure 6 *Frequency distribution of air quality votes.*

V = mean air velocity, fpm (m/s); $V < 23.6$ fpm (0.12 m/s).

a, b, and c = constants shown in Table 3.

This correlation can be used to calculate the measured neutral temperature, i.e., T for $TS = 0$. The neutral temperature can also be predicted from Fanger's comfort (PMV) equation. Table 2 shows the measured and predicted neutral temperatures together with the difference in neutral temperature between them. (Note that the neutral temperature given by the correlation for rooms A through E differs from the weighted average of the neutral temperatures for these rooms. This is because the indoor environment in naturally ventilated offices could not be controlled precisely. As a result, the range and the distribution of indoor air temperature and velocity vary with rooms.) It can be seen that Fanger's equation overpredicts the neutrality for rooms A, B, D, and E and for the foot level in room C due to various reasons mentioned above, which seems to confirm the findings by Schiller et al. (1988) and Brager (1992).

TABLE 3
Constants a, b, c, and Correlation Coefficient r for Equation 1

Room	Data sets	Level	a	b	c	r*	Range of T
			For I-P units				
A	44	head	0.3112	0.1162	21.09	0.66	68.2 - 79.2
		foot	0.3160	0.0628	21.48	0.63	63.9 - 75.2
		overall	0.3385	0.1182	22.82	0.68	67.5 - 76.8
B	26	head	0.2943	0.0	21.30	0.64	70.0 - 78.4
		foot	0.3738	0.0	25.70	0.63	67.3 - 73.2
		overall	0.3719	0.0	26.46	0.65	69.3 - 75.9
C	33	head	0.3729	0.0	27.49	0.77	74.1 - 81.5
		foot	0.3117	0.0	21.82	0.64	72.1 - 79.7
		overall	0.3577	0.0	25.92	0.79	73.6 - 80.8
D	30	head	0.1921	0.0	14.03	0.77	70.7 - 88.5
		foot	0.2627	0.0	18.85	0.81	67.6 - 83.1
		overall	0.2471	0.0	18.01	0.80	69.6 - 84.9
E	30	head	0.2658	0.0	18.60	0.67	67.3 - 76.6
		foot	0.2523	0.0	17.62	0.56	64.8 - 73.6
		overall	0.2631	0.0	18.53	0.65	68.1 - 75.6
A to E	163	head	0.2033	0.0	14.44	0.67	67.3 - 85.6
		foot	0.2588	0.0	18.07	0.72	63.9 - 81.3
		overall	0.2481	0.0	17.62	0.73	68.1 - 83.1
			For SI units				
A	44	head	0.5602	22.88	11.13	0.66	20.1 - 26.2
		foot	0.5688	12.37	11.37	0.63	17.7 - 24.0
		overall	0.6094	23.27	11.98	0.68	19.7 - 24.9
B	26	head	0.5297	0.0	11.89	0.64	21.1 - 25.8
		foot	0.6729	0.0	13.76	0.63	19.6 - 22.9
		overall	0.6695	0.0	14.56	0.65	20.7 - 24.4
C	33	head	0.6712	0.0	15.56	0.77	23.4 - 27.5
		foot	0.5611	0.0	11.85	0.64	22.3 - 26.5
		overall	0.6439	0.0	14.47	0.79	23.1 - 27.1
D	30	head	0.3458	0.0	7.88	0.77	21.5 - 31.4
		foot	0.4728	0.0	10.44	0.81	19.8 - 28.4
		overall	0.4447	0.0	10.10	0.80	20.9 - 29.4
E	30	head	0.4784	0.0	10.08	0.67	19.6 - 24.8
		foot	0.4541	0.0	9.55	0.56	18.2 - 23.1
		overall	0.4736	0.0	10.11	0.65	19.0 - 24.2
A to E	163	head	0.3660	0.0	7.93	0.67	19.6 - 29.8
		foot	0.4658	0.0	9.79	0.72	17.7 - 27.4
		overall	0.4466	0.0	9.68	0.73	19.0 - 28.4

* corrected for multiple correlation

They found that the predicted neutral temperature was on average 4.3°F (2.4 K) higher than that measured for 304 office workers in 10 buildings, which could be attributed to the inaccurate estimation of the metabolic rate and clothing value used in the PMV equation (Brager et al. 1993).

In Figure 7 the occupant's thermal sensation responses are presented as a function of mean air temperature using the measured mean air velocities for room A. The PMV lines predicted from Fanger's equation are also presented for comparison (assuming a metabolic rate of 1.2 met and clo values indicated in Table 2 and using the average values of the measured air velocity and radiant temperature for the corresponding rooms). Note that a PMV line is theoretically not a straight line, but, because the curvature is very small, the error caused by linearizing the curve is negligible in the region close to the comfort temperature. Figure 7 indicates that the data lines from the present investigation are steeper than those given by Fanger's equation, suggesting the occupants are more sensitive to changes of air temperature. This fact was also observed by Fishman and Pimbert (1979) whose field study showed that the gradient of their data curve deviated from Fanger's equation particularly at temperatures above 75.2°F (24.0°C). In addition they also found that Fanger's comfort equation predicted the neutral temperature 1.1°F (0.6 K) higher than that obtained from the field survey, which was attributed to the incorrect estimation of the subjects' clothing. The deviation appears to be wider at foot level than at head level.

It is also noted that for rooms A, B, C, and D the neutral temperature for the head level is between 1.8°F (1.0 K) and 3.8°F (2.1 K) higher than that for the foot level. This seems to disagree with the common belief concerning the comfort requirement of warm feet and cold head. For measurements conducted in cold seasons, one reason for this disagreement may be the variation in radiation distribution. Because windows of the rooms are close to head level while heaters are below head level, the radiant temperature at head level would be lower than that at foot level. The measured air temperature at head level was higher than that at foot level due to thermal stratification. The head would thus have lost more heat due to radiation but less than the feet due to convection. However, the radiation has not been incorporated into the above correlation for thermal sensation as the radiant temperature was measured in the middle of the rooms but not at head and foot levels. Hence, the effect of radiation on the occupant was not evaluated for local comfort prediction. Another reason for the disagreement might be the adaptation of the occupant to the neutrality, i.e., the occupant's adjustment to the surrounding temperature. In rooms A, B, C, and D, the subjects concerned are the normal occupants and could have been accustomed to their usual environment and hence tolerated a slight vertical temperature difference. This is shown by the fact that most of the thermal sensation votes give the same ratings of room environment at head and foot levels despite the fact that there was always a positive vertical temperature difference. Table 2 also shows that the average vertical temperature difference for these four rooms is between 2.2°F (1.2 K) and 3.8°F (2.1 K). If the subjects had not been the normal occupants and had been used to an environment without such a temperature stratification, it can be postulated that they may have voted the thermal sensation such that the neutral temperature at foot level was similar to that at head level. This is true in room E, where the subjects are not the normal occupants and the neutral temperature obtained for the head level is the same as that for the foot level, although this might be due to the large velocity difference between foot and head levels. In circumstances where the parameters that influence the thermal sensation are uniform, it may be inferred that people would like to have the same temperature at head and foot levels. The preference for warm feet and a cold head may result from the non-uniformity of air temperature as well as radiant temperature. In most offices, there is a positive temperature stratification so that occupants will prefer a higher temperature at foot level (warm feet) if the head level is already at the neutral level and a lower temperature at head level (cold head) if feet are at a comfortable temperature. Another cause for the preference of warm feet and cold head may be the non-uniformity of velocity distribution. Air velocity at foot level is often higher than that at head level, as found from this investigation. Therefore, the air temperature at foot level should be higher to maintain the same neutrality as that at head level.

It can also be seen from Table 2 that the measured indoor air temperature is higher than the neutral temperature by an average of 3.6°F (2.0 K) for the five rooms and 1.6°F (0.9 K) for rooms A, B, and E in which measurements were carried out in heating seasons. This indicates that these rooms and the building with central heating as a whole were overheated during the heating seasons.

Air Movement Figure 5 shows that the overall impression of the air movement was on the side of being stagnant. For room A, when a window and/or the door were partly opened, the impression of air movement shifted to being slightly drafty (Croome et al. 1992). The main cause of the draft, was considered to be low temperature as air velocity and turbulence intensity were not high.

The ratings of the air movement (AM) are associated with the air temperature and velocity as follows.

In I-P units:

head level:

$$AM = 0.0452\, T - 0.024\, V - 2.54 \quad (r = 0.31) \quad (2)$$

foot level:

$$AM = 0.0786\, T - 5.20 \quad (r = 0.34) \quad (3)$$

overall:

$$AM = 0.0592\, T - 0.018\, V - 3.62 \quad (r = 0.30) \quad (4)$$

where T is the mean air temperature, °F, and V is the mean air velocity, fpm.

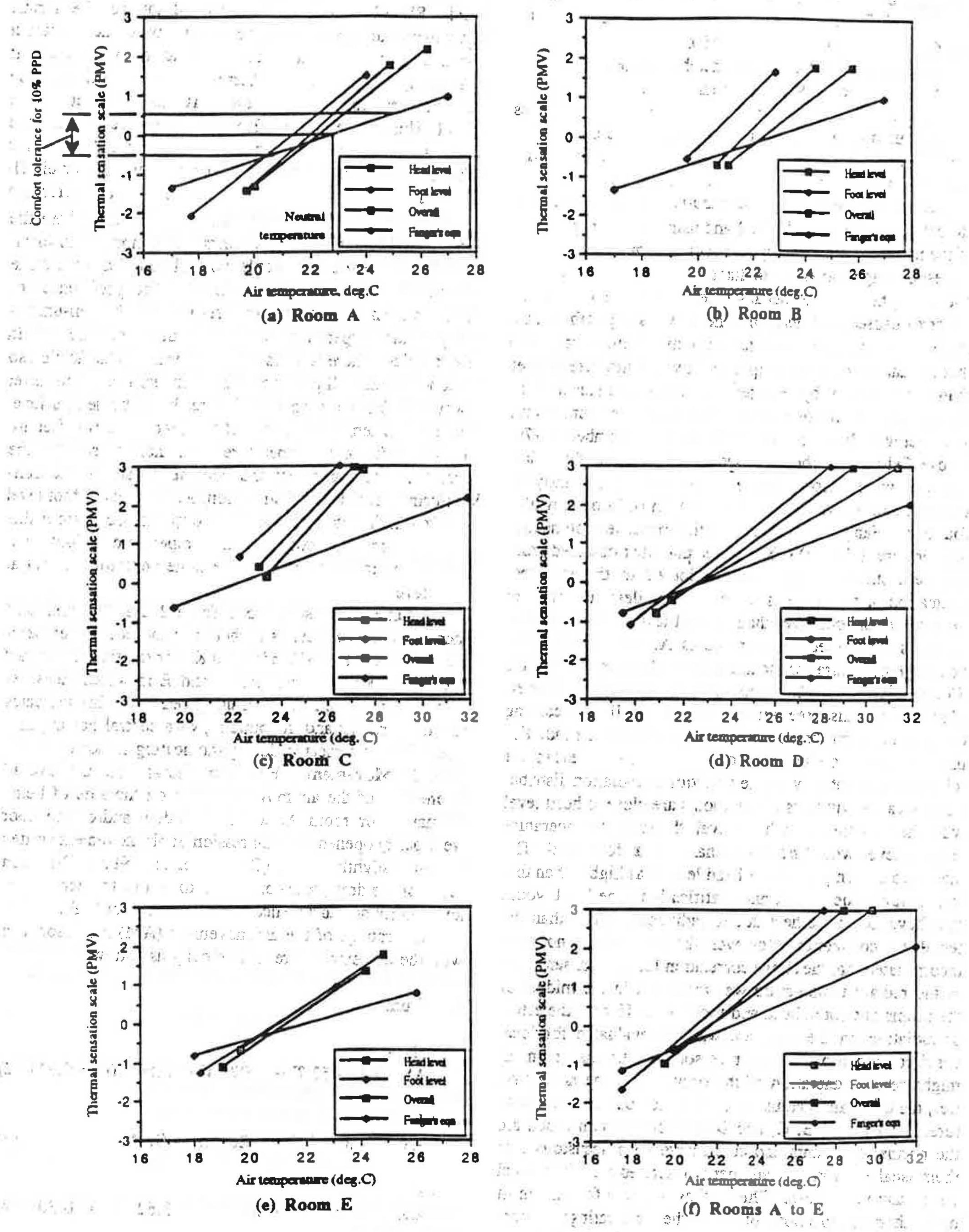

Figure 7 *Effect of air temperature on thermal sensation responses.*

In SI units:

head level:
$$AM = 0.0814\,T - 4.75\,V - 1.09 \quad (r = 0.31) \qquad (2)$$

foot level:
$$AM = 0.1415\,T - 2.68 \quad (r = 0.34) \qquad (3)$$

overall:
$$AM = 0.1066\,T - 3.50\,V - 1.72 \quad (r = 0.30) \qquad (4)$$

where T is in °C and V in m/s.

The above equations indicate that the draft risk increases (i.e., AM decreases) with an increase in air velocity but with a decrease in air temperature. The effect of turbulence intensity on the air movement votes was found statistically insignificant. 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. The calculated comfortable temperature is less than 68.0°F (20.0°C) for the head level, foot level, and overall judgment. Hence, the preferred indoor temperature for air movement is lower than that for thermal sensation for air velocities measured in the present investigation.

Figure 5 and Equations 2 through 4 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 draft. In these tests the feet were more sensitive to air temperature but less sensitive to air velocity than the head.

Odor Intensity Odor was detectable in most cases (see Figure 6). However, no satisfactory correlation between odor 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 odor was still perceivable, while in other cases, when the CO_2 level was higher than 1,000 ppm, the odor intensity was rated as not detectable. This seems to suggest that there were other pollution sources, such as building materials or furnishings, that could be more significant than the odor emission from the occupants. The judgment could also be affected by fatigue of the olfactory sense.

Air Freshness Figure 6 also shows that the rating of air freshness was, in general, slightly stuffy. Air freshness for these rooms can be related to the air temperature, velocity, and turbulence intensity in the following form.

In I-P units:

$$AF = 0.0243\,T - 0.013\,V - 0.0079\,Tu - 0.78 \quad (r = 0.47) \qquad (5)$$

where

T = mean air temperature, °F;
V = mean air velocity, fpm;
Tu = turbulence intensity, %.

In SI units:

$$AF = 0.0438\,T - 2.59\,V - 0.0079\,Tu \quad (r = 0.47) \qquad (5)$$

where T is in °C and V in m/s.

Hence air freshness increases (i.e., AF decreases) as the air temperature decreases or as the air velocity or turbulence intensity increases. Bedford (1948) pointed out that a cool room tended to feel fresh and an overheated one stuffy. He also considered that the impression of freshness was due to the local stimulations of the skin by the environment, partly thermal and partly tactile. The former is related to air temperature and the latter may be affected by air velocity and turbulence intensity (i.e., the fluctuation of velocity over the mean value).

The assessment of odor intensity and air freshness shows that the air change rate is not a good indicator of indoor air quality since the supply air could be contaminated or not well distributed in the breathing zone.

ENERGY SAVING POTENTIAL

Since the measured indoor air temperature and the neutral temperature given by Fanger's equation are higher than the neutral temperature from field measurements, energy can be saved through decreasing room temperature in heating seasons. The potential for energy savings is described as follows.

In most office buildings, heat losses in cold seasons are mainly due to conduction and ventilation. These heat losses are proportional to the temperature difference between indoors and outdoors ($T_i - T_o$). Thus, for a current room temperature setting in heating seasons, the amount of heat loss, q_c, is

$$q_c \propto (T_{ic} - T_o), \qquad (6)$$

and for the temperature setting based on the desired neutrality from field measurements, the heat loss, q_d, is

$$q_d \propto (T_{id} - T_o) \qquad (7)$$

where T_{ic} and T_{id} are the current room temperature setting and desired room temperature, respectively.

The amount of energy saving is then

$$(q_c - q_d) \propto (T_{ic} - T_{id}). \qquad (8)$$

Hence the ratio of energy saving based on the desired room temperature is

$$(q_c - q_d)/q_d = (T_{ic} - T_{id})/(T_{id} - T_o). \qquad (9)$$

In the U.K. the average outdoor temperature during the heating season, T_o, is about 42.8°F (6.0°C) and for the whole year is 50.0°F (10.0°C). Assuming the desired room temperature for neutrality is 71.0°F (21.7°C), the ratio of energy saving is obtained for several differences between current and desired room temperatures, and this is given in Table 4.

It is seen that lowering room temperature by 1.8°F (1.0 K) represents about 6.4% and 8.5% reductions in space heating use for T_o = 42.8°F (6.0°C) and T° = 50.0°F (10.0°C), respectively. For a temperature reduction of 1.6°F (0.9 K), the mean value measured for rooms A, B, and E, the potential of energy saving is 5.7% for T_o = 42.8°F (6.0°C) and 7.7% for T_o = 50.0°F (10.0°C), and for a temperature reduction of 2.5°F (1.4 K), the maximum value measured for the head level in room B, the corresponding energy saving potential is 8.9% and 12.3%. To take full advantage of this saving, it is necessary to control the heat supply to an office by installing an individually adjustable thermostat.

CONCLUSIONS

A limited investigation on thermal comfort and air quality in naturally ventilated offices has shown that thermal sensation, air movement, and air freshness are generally dependent on the air temperature, velocity, and turbulence intensity. When the indoor air temperature is substantially higher or lower than the neutral temperature, it is the predominant factor that decides the occupant's response to thermal comfort and air freshness.

From the present investigation, it seems that the thermal models based on laboratory tests at steady-state conditions cannot accurately predict the thermal environment for naturally ventilated offices where the climatic conditions are transient and where the occupants invariably change their activities. For the cases investigated, Fanger's equation for thermal comfort generally overpredicts the neutral temperature and underpredicts the comfort requirement when air temperature deviates from neutrality. However, further work is needed to verify the comfort models based on the field measurements for a wide range of subjects.

To achieve good indoor climate and air quality in a naturally ventilated office, it is necessary to supply sufficient fresh air to the breathing zone either by opening windows or by installing a suitable vent. The size of the vent opening should ideally be controlable, either manually or by an odor sensor, so that the indoor air will be invigorated, the odor reduced or eliminated, and the air freshness enhanced.

Heating energy can be saved by lowering the room temperature during heating seasons. Besides, a lower indoor temperature can reduce the occupant's complaints about the feeling of stuffiness.

TABLE 4
Energy Savings Due to Lower Room Temperature

$(T_{ic} - T_{id})$	$(q_c - q_d)/q_d$ (%) for T_{id} = 71.0°F (21.7°C)	
°F (K)	T_o = 42.8°F (6.0°C)	T_o = 50.0°F (10.0°C)
0.9 (0.5)	3.2	4.3
1.3 (0.7)	4.5	6.0
1.6 (0.9)	5.7	7.7
1.8 (1.0)	6.4	8.5
2.0 (1.1)	7.0	9.4
2.5 (1.4)	8.9	12.3
3.6 (2.0)	12.7	17.1

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APPENDIX A

Test Conditions for Indoor Climate Investigation

Date ______________ Time ______________

Room dimension (m):

Window: 1 2 3 4

Location:
Dimension:
Temperature (°C):
Opening level: full/part open/shut

Door opening: full/part open/shut

Wall surface temperature (°C):

West : East:
South: North:
Floor: Ceiling:

Air inlet: 1 2 3 4

Face:
Location:
Temperature (°C):
Velocity (m/s):
RH (%):

Air exit: 1 2 3 4

Face:
Location:
Velocity (m/s):
RH (%):

Heater: 1 2 3 4

(a) on: Face:
Location:
Temperature (°C):

(b) off

Obstruction: 1 2 3 4

Location:
Dimension:
Temperature (°C):

Occupant: 1 2 3 4

Location:

Other heat sources:

Comfort meter:

Clo: Met: Vap. pres. (kPa):
PMV: PPD: etc.

Indoor climate analyser:

Air temperature (°C):
Radiation:

Pl. rad. temp. (°C): A: B:
Asymmetry (W/m^2): A: B:
Incident power (W/m^2): A: B:
Air velocity (m/s): Mean: Sd:
Humidity: RH (%):
Vap. pres. (kPa):
Dew pt. (°C):

Outdoor climate:

Weather conditions: Sunny/cloudy/windy/rain
Wind data: Speed (m/s): Direction (degree):
Air: Temperature (°C): RH (%):

Air change rate:

APPENDIX B
Questionnaire for Subjective Survey of the Indoor Environment

Date _______________ Time __________

Building/Room ______________________________

Occupant: Nationality ____________ Age ________

Please answer the following questions by circling 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 drafty	(a) too drafty	(a) too drafty
(b) drafty	(b) drafty	(b) drafty
(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 odor?

(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: