Discomfort Caused by Vertical Air Temperature Differences

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Abstract

Sixteen subjects (8 females and 8 males) each partipated in four experiments. In a test room each subject was exposed to four different vertical air temperature differences (0.4K, 2.5K, 5.0K, 7.5K) between head level and ankle level with highest temperature at head level.

In the first experiment in an approximately uniform environment (vertical air temperature difference 0.4K) the preferred ambient temperature was determined for each subject by adjusting the ambient temperature according to his wishes. Each experiment lasted 3 hours.

In the remaining three experiments the temperature level at the centre of the body was for each subject during the first 1½ hour maintained at his preferred ambient temperature identified in the first experiment. During the last 1½ hour the temperature level was changed according to the subject's request. The air temperature difference between head and ankles remained the same (2.5K, 5.0K or 7.5K).

The subjects were sedentary and wore a light standard clothing (0.6 clo). Subjective judgements of the thermal sensation, local discomfort, and skin temperatures were recorded.

A curve has been established showing the percentage of people feeling discomfort due to a vertical temperature difference between head level and ankle level. Less than 5-10% of the population is predicted to feel uncomfortable due to a vertical air temperature difference if the difference is less than 3-4K.

The thermal sensation votes showed that discomfort was attributed to warm head and/or cold feet.

Introduction

The purpose of the present study is to determine the limits for the vertical air temperature difference between head and ankle level to which man in thermal neutrality can be exposed without feeling discomfort.

Thermal neutrality for a person is defined as a condition in which he prefers neither a higher nor a lower ambient temperature level. Thermal neutrality depends on the activity and clothing and on the climate parameters: air temperature, mean radiant temperature, relative air velocity and humidity. Fanger's comfort equation (1) predicts the combinations of activity, clothing and climate parameters that will provide thermal neutrality. Thermal neutrality is a necessary condition for a person to obtain thermal comfort. However, this condition is not always sufficient. It is a further requirement that no local warm or cool discomfort is experienced on any part of the body.

Local thermal discomfort can be created by asymmetric thermal radiation, draught, cold or warm floor, non-uniform clothing and by vertical air temperature difference which in the present paper will be defined as the difference between the air temperature 1.1m (head level for sedentary person) and 0.1m (ankle) above the floor level. The local discomfort caused by a vertical air temperature difference may either be warm discomfort at the head or cold discomfort at the feet (or both).

Very few investigations on the influence of a vertical air temperature difference have been reported in the literature.

McNair and Fishman (2,3) exposed 48 sedentary subjects to four air temperature differences: 0, 1.3, 2.7 and 4.0K difference between head (1.1m) and ankles (0.1m). The subjects were exposed for only one hour. The authors concluded that the subjective effect of vertical air temperature differences, as indicated by the differences between the thermal sensations of the head and feet, is slight, and hence for all practical purposes insignificant.

Eriksson (4) tested 15 sedentary subjects exposed to vertical air temperature differences in tractor cabins. The subjects wore heavy outdoor clothing (1.5-2.0 clo). The author concluded that positive differences, i.e., higher air temperature at head level than at ankle level would cause discomfort if they exceeded 4-6K. Negative differences, i.e., highest air temperature at ankle level, would cause discomfort if they exceeded 6-8K.

In the present experiments only positive air temperature differences (highest temperature at head level) were investigated, which is the case occurring most frequently in buildings in practice.

Experimental Method

In a specially designed climatic chamber, each subject participated in 4 experiments lasting 3 hours, one in an approximately uniform environment (0.4K temperature difference between head and ankle level), and then three experiments with air temperature differences of 2.5, 5.0 and 7.5K between head and ankle level. During the experiments subjective votes were recorded.

Experimental Facilities

A special test room was build (LxWxH: 2.0x1.4x2.0m) at the Laboratory (Fig. 1). The temperature of all surfaces in the test room, except the wall with the door,

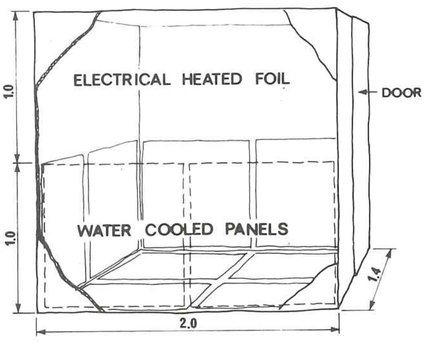

Figure 1. The test room with upper walls and ceiling comprising electrical heated foil and floor and lower walls water-cooled panels. The front wall, including a door, was made of plastic foil (polyvinylchloride).

were controlled. The ceiling and the upper walls were heated by electrical foil. The floor and lower walls were cooled by water-filled panels. The room was installed in a large hall, where the temperature was controlled at approximately 21°C. All surfaces, except the wall with the door, were covered with aluminium foil to reduce the radiant emission and therefore the vertical difference in radiant temperature.

The front wall and door consisted of a double layer of transparent plastic foil (PVC). The test room was illuminated through this wall, and it was also possible to hold a conversation between the subject and the operator.

The other surfaces were well insulated from the surroundings. Through small openings in the floor and in the ceiling it was possible to maintain a slight air change in the room. This air flow also ensured that the natural convection from the subject did not create air movements in the test room, which would destroy the air temperature difference between head and ankles.

The humidity was not controlled; however, this exerts only a minor influence. The water vapour pressure varied in the present experiments between 1.32 and 1.47 kPa.

During all experiments the air temperature was measured with small thermoelements at 11 levels between 0.05m and 1.95m above floor level. The surface temperature of the walls, ceiling and floor were also measured. The globe temperature (6 in. globe) was measured 1m above the floor (Fig. 2).

The subject was sedentary on a raised chair, his centre being 1m above the floor (Fig. 2). In all experiments the vertical air temperature increased appro-

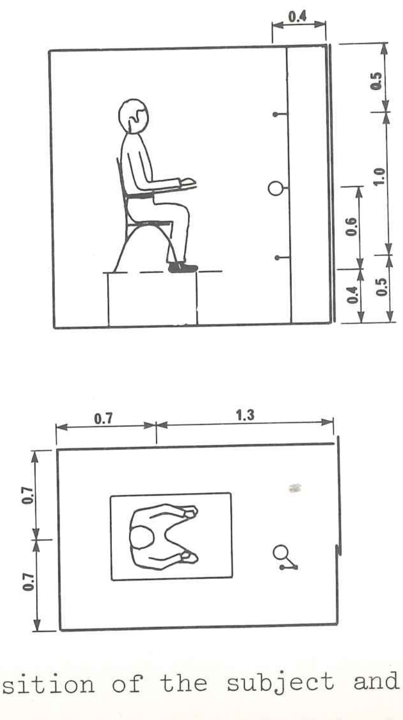

Figure 2. The position of the subject and the equipment for measuring air temperature and globe temperature.

ximately linearly between 0.4m to 1.6m above the floor level and the air temperature measurements 0.5m and 1.5m above the floor (Fig. 2) was used to calculate the temperature difference between head level and ankle level.

Subjects

Sixteen college-age persons (eight males and eight females) were used as subjects. Only persons in good health were allowed to participate. All subjects were volunteers who were paid for participating in the experiments. Each subject participated in four experiments (3h). All subjects were clothed in the KSU-standard uniform (6), which simulates a light clothing ensemble with a clo-value of 0.6, comprising a cotton twill shirt and trousers, cotton under-shorts and cotton sweat socks. In addition, the subjects wore light open sandals (not part of the KSU-uniform). The anthropometric data for the subjects are listed in Table 1.

	No. of subjects	Age Years	Height m	Weight kg	DuBois area m^2
Females	8	21 ±2*	1.69 ±.05	60.9 ±4.8	1.7 ±.1
Males	8	22 ±2	1.82 ±.07	69.8 ±7.9	1.9 ±.1
Females + Males	16	21 ±2	1.75 ±.09	65.3 ±7.8	1.8 ±.1

*Standard deviation of the sample.

Table 1. Anthropometric data for the subjects.

Experimental Procedure

The subjects were each exposed to four different air temperature differences between head and ankle (0.4K, 2.5K, 5.0K, 7.5K) on four different days. The first experiment was always in the approximately uniform environment (0.4K) but the order of the three remaining experiments was balanced between the subjects. Each subject reported in good time prior to the commencement of the experiment. It was ascertained that he had had sufficient sleep during the previous night, had no fever and had not consumed alcohol during the previous 24 hours. The subject put on the clothing and entered the chamber where he was seated.

In the first experiment the preferred ambient temperature was determined for each subject. At the beginning of the first experiment the air temperature (1m above the floor) was set at approximately 21°C. McIntyre (7) has shown that the preferred temperature level after a couple of hours is not influenced by the temperature level at the beginning of the experiment.

Since it was important that the environment was kept thermally neutral for the subject, the ambient temperature was adjusted according to his requests. This was done by asking the subject each 10 min. according to the questions in Fig. 3.

At the same time air temperatures, surface temperatures and globe temperature were measured. The experiment was finished after 3 hours in the test room. The preferred temperature was estimated as the mean value during the last 30 minutes.

During the three remaining experiments the procedure was slightly different. The temperature level in the beginning was for each subject set at his preferred ambient temperature identified in the first experiment. The temperature level (preferred ambient temperature) was maintained at the centre of the subject (1.0m above the floor), and the difference between the air tempera-

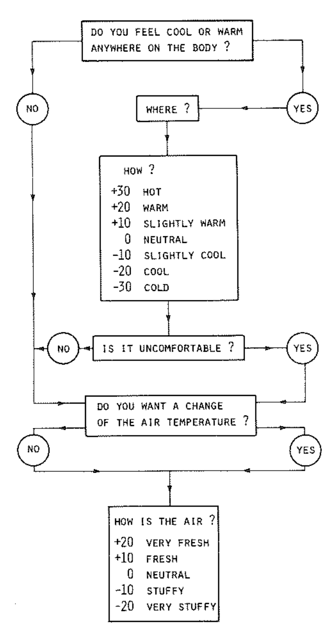

Figure 3. Questions for evaluating subjects' response to a vertical air temperature difference.

ture 1.0 and 0.5m above the floor was the same as that between 1.5 and 1.0m above the floor.

During the first 90 minutes of each experiment this temperature level was maintained constant, even if the subject wanted a temperature change. During the last 90 minutes of each experiment the temperature level was changed according to the subject's request, but the air temperature difference between head and ankles remained the same.

As in the first experiment the subject was asked to answer the questions in Fig. 4 each 10 minutes, and at the same time all temperatures were recorded.

During the experiments the subject was kept occupied by reading. It was prohibited to eat or drink while the test was in progress, whereas moderate smoking was allowed.

Thermal Manikin

The thermal manikin developed by Madsen (5) has a shape which simulates approximately the body of a normal human being. It consists of a thin shell of fibreglass reinforced polyester. The manikin is divided into 16 sections, each being electrically heated internally. Thermostats control the skin temperature of each section at $\sim 33.7^{\circ}C$. The heat loss, equal to the energy supply, is measured for each of the 16 sections.

The manikin, clothed in the 0.6 clo standard uniform, was seated in the same chair as the subjects, and the heat loss from the different parts of the body was first measured in the uniform environment (0.4K difference between head and ankle level). The manikin was then exposed to the same three temperature differences as the subjects. The temperature at the centre of the body was maintained constant. In each condition the heat loss from the different parts of the manikin was measured.

Results

Preferred Temperature

In the first experiment, where the air temperature and surface temperatures were changed according to the subjects' wishes, the preferred air temperature was estimated as the mean value of the three last measurements (last half hour of the experiments). The mean values for females and males are listed in Table 2.

Sex	Preferred air temperature (°C)			
	Vertical air temp. difference			
	0.4 K	2.5 K	5.0 K	7.5 K
Females	23.9 ±0.8*	24.5 ±0.9	24.1 ±0.9	24.5 ±1.2
Males	24.0 ±0.8	24.8 ±0.9	24.7 ±1.0	24.8 ±0.8
Females and Males	23.9 ±0.8	24.6 ±0.9	24.4 ±1.0	24.6 ±1.0

*Standard deviation of the sample.

Table 2. Preferred air temperatures at 1.0m above the floor (centre of the body). Mean values during the last half hour of the experiments.

The walls, floor and ceiling had an emissivity estimated to be 0.1, except for the wall in front of the subject including the door. This wall and the door were made of two layers of plastic (PVC) with an emissivity equal to 0.9. As the radiation area of the subject (approx. $1.3m^2$) was small compared to the area of the reflecting surfaces ($16.4m^2$), the reflection of the radiation emitted by the subject (temperature of the clothing surfaces $\sim 29^{\circ}C$) had only a small influence on the mean radiant temperature. The mean radiant temperature was dominated by the temperature of the plastic wall. Calculations and measurements show that the mean radiant temperature was less than 0.2K higher than the air temperature at the centre of the test room.

In the three experiments with large air temperature difference the preferred air temperature at the centre of the subject was significantly (5%) higher than in the approximately uniform environment (Table 2). The difference was 0.7K at a vertical air temperature difference of 2.5K and 7.5K, but with a vertical air temperature difference of 5.0K the preferred air temperature was only 0.4K higher.

To estimate the difference between the radiation at head level and at ankle level the globe temperature was measured 0.5, 1.0 and 1.5m above the floor, i.e. at ankle level, centre level and head level of a sedentary subject. The results are shown in Table 3, for an air temperature difference between head and ankle of 5K. The globe temperature difference was approximately 0.6 times the air temperature difference.

To estimate the radiation asymmetry the room was divided into an upper and a lower half-room by a horizontal plane 1.0m above the floor (centre of the subject). The asymmetry is expressed as the difference between the radiant temperature of the two half-rooms. The radiant temperature of a half-room is defined as

Level above the floor m		Measured: Air temp. °C	Measured: Globe temp. °C	Calculated radiant temp. of a half room
0.5 (ankles)	lower half room	19.5	20.6	20.6
1.0 (centre)		22.0	22.1	
1.5 (head)	upper half room	24.5	23.8	24.0
Vertical temp. diff.		5.0K	3.2K	3.4K

Table 3. Measurement of the vertical air- and globe temperature difference and the calculated radiant temperature (in relation to a sedentary subject) of the upper and lower half-room. The data refer to an air temperature difference of 5K between head and ankle.

that uniform temperature of a half-room that would provide the same radiant heat exchange between the human body and the half-room as in the actual case. From the measured air- and globe temperatures (Table 3) the radiant temperature of the upper and lower half-room was calculated (Table 3). The radiant temperature difference between the two half-rooms (3.4K) was 0.7 times the vertical air temperature difference (5K).

Local Sensation and Discomfort

The number of subjects feeling discomfort was estimated for the third half hour (60-90 min.), i.e. during the end of the period, where the air temperature was not changed, and for the last half hour (150-180 min.), i.e. during the end of the period, where the air temperature had been changed according to the subjects' wishes. A subject was estimated to be uncomfortable if he voted uncomfortable (Fig. 3) twice out of three times in a half hour period. The numbers and percenta-

Vertical air temp. diff. K	Sex	After 90 min occupancy				After 180 min occupancy			
		Dissatisfied subjects		Thermal sensation vote		Dissatisfied subjects		Thermal sensation vote	
		Number	%	Head	Feet	Number	%	Head	Feet
0.4	Females	0		-0.4 ±5.2*	-1.9 ±6.4	0		0.0 ±1.9	-0.9 ±2.0
	Males	1		0.4 ±6.4	-2.8 ±4.3	0		-0.5 ±2.0	-1.8 ±3.1
	Females + Males	1	6.3	0.0 ±5.6	-2.3 ±5.3	0	0	-0.3 ±1.9	-1.3 ±2.6
2.5	Females	1		3.2 ±5.1	0.8 ±4.7	0		3.8 ±4.1	0.5 ±3.0
	Males	2		0.6 ±3.1	-3.6 ±3.5	1		0.6 ±2.8	-2.6 ±3.9
	Females + Males	3	18.8	1.9 ±4.3	-1.4 ±4.6	1	6.3	2.2 ±3.8	-1.1 ±3.7
5.0	Females	3		7.1 ±5.2	0.8 ±3.5	0		3.5 ±4.4	-1.4 ±2.0
	Males	3		4.4 ±3.5	-2.3 ±3.0	2		4.3 ±6.2	-3.3 ±4.1
	Females + Males	6	37.5	5.8 ±4.5	-0.8 ±3.5	2	12.5	3.9 ±5.2	-2.3 ±3.2
7.5	Females	4		10.8 ±5.9	0.5 ±6.3	4		9.3 ±5.5	-5.8 ±5.0
	Males	3		5.8 ±3.8	-3.6 ±3.8	7		7.5 ±2.7	-5.3 ±3.3
	Females + Males	7	43.8	8.3 ±5.5	-1.6 ±5.5	11	68.8	8.4 ±4.3	-5.5 ±4.1

*Standard deviation of the sample.

Table 4. The number of subjects voting uncomfortable and the mean thermal sensation votes (all subjects) for the head and feet during the third half-hour (60-90 min.) and the last half-hour (150-180 min.) of the experiment.

ges of subjects feeling discomfort, and the mean votes for the local thermal sensations of all subjects (Fig. 3), are listed in Table 4.

To analyse why the subjects voted uncomfortable, the thermal sensation for the head and the feet was calculated in Table 5.

Sex	Mean thermal sensation vote for subjects voting uncomfortable							
	Third half hour (60-90 min)				Last half hour (150-180 min)			
	Number	Head	Feet	Head-Feet	Number	Head	Feet	Head-Feet
Females	5	11.0±4.2*	3.0±5.7	8.0±5.7	5	11.0±3.9	-7.4±5.3	18.4±4.8
Males	4	1.3±8.3	-5.2±3.4	6.5±5.5	7	6.0±1.6	-5.4±4.1	11.9±3.5
Females +Males	9	6.7±7.8	-0.7±6.3	7.3±5.3	12	8.1±3.7	-6.3±4.5	14.6±5.2

*Standard deviation of the sample.

Table 5. Mean local thermal sensation for the subjects who voted uncomfortable. The mean thermal sensation was estimated at the lowest vertical air temperature difference, where the subject voted uncomfortable (scale, see Fig. 3).

In Fig. 4 regression lines (based on a probit analysis) show the percentage of subjects feeling discomfort after 90 minutes of occupancy and after 180 minutes of occupancy. The regression lines for discomfort intersect the ordinate axis at 7% for 90 minutes occupancy and 0.3% for 180 minutes of occupancy, i.e. 7% and 0.3% respectively are predicted to be uncomfortable when the thermal environment is uniform. With increasing air temperature difference, any increment in the percentage of those experiencing discomfort above 7 or 0.3% must have been caused by thermal non-uniformity created by the vertical air temperature difference.

The regression line for 180 minutes of occupancy applies for thermal neutral subjects. If it is accepted that 5% feel uncomfortable due to a vertical air tempe-

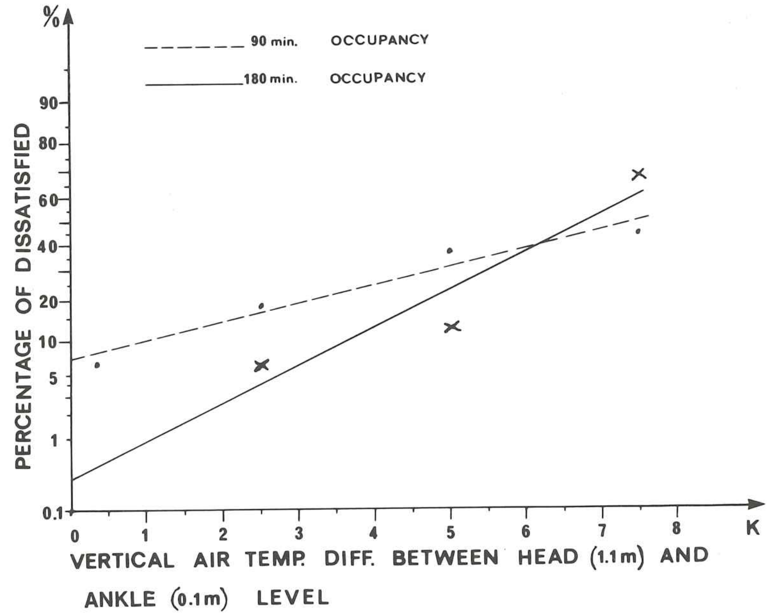

Figure 4. Probit analysis of the subjective responses concerning local thermal discomfort.

rature difference, Fig. 4 shows that the air temperature difference between head and ankles should be less than 2.8K. If 10% dissatisfied is accepted, the limit is 3.7K

Table 6 shows the mean votes for the freshness of the air after 90 minutes and 180 minutes of occupancy. The subjects felt the air significantly more stuffy with a temperature difference between head and feet of 5.0K and 7.5K than in the uniform environment (0.4K).

Air temp. difference between head and ankle (K)	Mean vote for freshness after 90 min	after 180 min
0.4	-0.9 ±3.1*	-1.2 ±3.6
2.5	-2.0 ±3.3	-2.7 ±3.4
5.0	<u>-4.4</u> ±4.1	<u>-4.8</u> ±4.1
7.5	<u>-5.8</u> ±3.6	<u>-4.1</u> ±3.3

*Standard deviation of the sample

___ significantly (5%) different from the uniform environment (0.4 K)

Table 6. Mean votes for 16 subjects of the freshness of the air (scale, see Fig. 3).

Measurements with Thermal Manikin

The percentual changes of the heat losses from the different regions when exposed to vertical air temperature differences are shown in Figure 5. The temperature difference decreased the heat loss from the hands, arms, head, chest and back, while the heat loss was increased from the feet, lower legs, thighs and abdomen. The change in the mean heat loss was less than 4%.

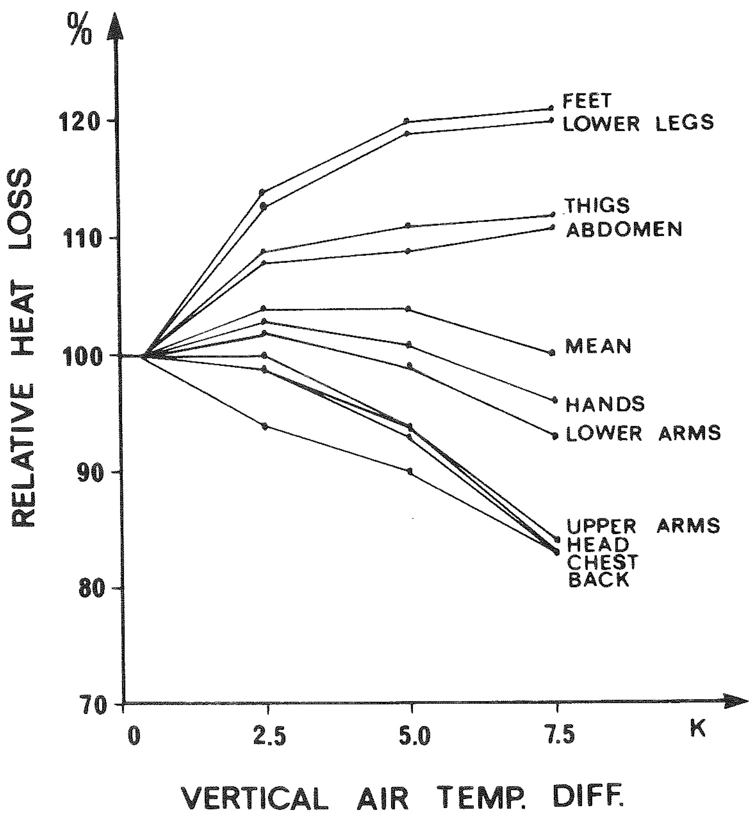

Figure 5. The percentual change of the heat loss from the different sections of the thermal manikin when exposed to vertical air temperature differences.

Discussion

The most important result of the present study is the curve in Fig. 4 predicting the percentage of people feeling uncomfortable due to a vertical air temperature difference between head and ankle level.

When estimating the comfort limits for a vertical temperature difference it is recommended to use the solid line in Fig. 4 for 180 minutes of occupancy, when the subjects feel thermally neutral for the body as a whole. During the first 90 minutes some of the subjects may have voted uncomfortable due to general warmth.

Table 3 shows that the subjects were also exposed to a difference in radiant temperature between the upper and lower half room. This difference was approximately 0.7 times the vertical air temperature difference. The solid line in Fig. 4 indicates that less than 5% of the subjects will be dissatisfied due to a vertical air temperature difference if the difference is less than 2.8K. This corresponds to a difference in radiant temperature between upper and lower half room equal to approximately 2K. Recent (as yet unpublished) studies at the Technical University of Denmark on discomfort from heated ceilings indicate that when the radiant temperature difference is less than 2K, less than 5% will be dissatisfied (due to warm head or cool feet). It is therefore likely that some of the discomfort expressed in the experiments have been caused by a difference in radiant temperature rather than a difference in air temperature.

If the radiant temperature of the upper and lower half room had been equal, the subjects would probably have tolerated a higher vertical air temperature difference.

A fixation of a limit for acceptable vertical air temperature differences is, strictly speaking, not possible on a purely scientific basis. The number of thermally uncomfortable people one is ready to accept is rather a socio-economic question. In spaces with a uniform thermal environment a minimum of about 5% of a group of people (uniform activity and clothing) can be expected to feel discomfort for the body as a whole (1). A percentage of persons feeling uncomfortable due to vertical air temperature difference of the order of magnitude would presumably be acceptable in most cases in practice. A figure of 5% feeling uncomfortable due to a vertical air temperature difference is therefore suggested as the criteria for spaces with high demands to the indoor climate.

In Fig. 4 five percent feeling uncomfortable after 180 minutes occupancy corresponds to an air temperature difference between head and ankles of 2.8K. If the subjects had not also been exposed to a vertical radiant temperature asymmetry it is likely that the 5% comfort limit for a vertical air temperature difference would have been higher than 2.8K. According to Fig. 4 10% dissatisfied corresponds to an air temperature difference equal to 3.7K (radiant temperature difference $\sim$ 2.6K).

Eriksson (4) concluded in his experiments that an increased vertical air temperature difference from 4K to 6K, raised the number of dissatisfied subjects from 14% to 43%. This is in fine agreement with the solid line in Fig. 4. In his experiments with subjects seated in a tractor cabin the clothing used was 1.5 clo which is much heavier than in the present experiments. The influence of the radiation is not reported by Eriksson.

The subjects in the experiments performed by McNair and Fishman (2,3) did not report any discomfort during exposure to air temperature differences up to 3-6K. But their exposure time was quite short (60 min.).

The reason for discomfort seems to be partly a feeling of warmth on the head and a feeling of cold on the feet (Table 5). Table 5 shows that discomfort occurs if the difference between the thermal sensation vote for the head and the feet is approximately 15 on the seven-point scale (-30, +30) which was used in the present experiments (Fig. 3).

The preferred air temperature in the uniform experiment (0.4K) was the same for females and males, 23.9^{o}C. The mean radiant temperature was approximately equal to the air temperature. The preferred air temperature was 1.6^{o}C lower than that predicted by Fanger's comfort equation (1).

The subjective sensation of freshness of the air was significantly (5%) decreased with increasing temperature difference between head and ankles. This is probably caused by the higher temperature around the head and is in agreement with other studies (8,9) which have indicated a greater freshness when the temperature of the inspired air decreased.

Conclusion

1. A curve (Fig. 4, solid line) has been established showing the percentage of people feeling discomfort due to a vertical temperature difference, with higher air and radiant temperature at head level than at ankle level. The curve applies for sedentary people, dressed in light clothing, who feel thermally neutral for the body as a whole.

2. It is suggested that the vertical air temperature difference, i.e. the temperature difference between head (1.1m above the floor) and ankles (0.1, above the floor) should not exceed 3-4K in spaces with high demands to the indoor climate. Less than 5-10% of the population is then predicted to feel uncomfortable due to a vertical air temperature difference.

3. Discomfort due to a vertical temperature difference was attributed to warm head and/or cold feet.

4. The subjective feeling of freshness of the air decreased with an increasing vertical air temperature difference.

Acknowledgement

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DISCUSSION

O.Nielsen
Danish Building
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You have found that a temperature difference between head and ankles less than 3-4K would not give more than 5-10 % uncomfortable.

This big difference surprises me, because my experiences from measuring in the field tell me that people complain of cold feet for differences smaller than 3-4K. But maybe it is caused by the girls not wearing cotton socks but nylon socks. Would you like to comment on that?

B.W. Olesen

The complaints of cold feet could be caused by vertical air temperature differences, cold floors, insufficient insulation on ankles and feet, by general thermal discomfort or by a combination of these factors. In practice many of the complaints of cold feet you find may be caused by a general sensation of cold, which first will be noticed at the extremities. And for the girls, the feeling of cold feet will be increased by a poor insulation of socks and footwear.

D.A.McIntyre
Electricity Council
Research Centre, UK

You quote your results as the percentage of people predicted to feel uncomfortable as a function of the vertical air temperature difference. However, each of your subjects was at his own individual preferred temperature. If a group of subjects are all at the same temperature, then at least 5 % are predicted to be thermally dissatisfied. How do you think the two discomfort distributions will combine?

B.W. Olesen

We cannot answer this question today. Further research is recommended to establish rules for predicting the total percentage of dissatisfied when general and various types of local discomfort occur at the same time.

M.Rolloos
Delft University of
Technology, NL

From the point of view of energy conservation it may be interesting to turn to local air conditioning of the working area in the office instead of conditioning the whole room at a certain temperature. But then research is necessary on both draught and vertical temperature gradient in combination with health influence.