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COMFORT LIMITS FOR HEATED CEILINGS

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INTRODUCTION

The purpose of the present study is to determine the limits of overhead radiation 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 is a necessary condition for a person to attain 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. Overhead radiation from a heated ceiling can create such local discomfort: either warm discomfort at the head or cold discomfort at the feet (or both).

The first systematic investigation of discomfort from heated ceilings was performed in the 1950's in England by Chrenko (1). He studied the subjective ratings of discomfort of test persons while they were exposed to a heated ceiling which could increase the mean radiant temperature by up to 12°C in a climate chamber. All the experiments took place at constant air temperature which means that the operative temperature was increased when the ceiling temperature was increased. Some of the discomfort votes given by his subjects might therefore have been caused by general warm discomfort for the body as a whole.

In later studies by McNall and Biddison (2) and by McIntyre and Griffiths (3) the increased temperature of the heated ceiling was balanced by a decrement of the wall temperature to maintain a constant operative temperature. This is not realistic, since in practice the air temperature is usually decreased to balance the increased ceiling temperature. Furthermore, since the subjects were tested in groups, all of them were not necessarily thermally neutral.

In the present experiments we have gone a step further in separating local discomfort due to the heated ceiling from general warm or cold discomfort for the body as a whole. This was done by keeping each individual subject thermally neutral throughout the experiment. This simulates many cases in practice where people return to the same space day after day (home and workplace) and aim at modifying their clothing to keep them thermally neutral. In the present experiments it was also decided to lower the air and wall temperature (rather than just the wall temperature) to keep the subjects neutral when exposed to overhead radiation. This was felt to be a more realistic simulation of most cases in practice.

As a supplement to the experiments involving subjects, a thermal manikin was used to measure the local heat losses of the different parts of the body when exposed to overhead radiation.

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RADIANT TERMS

To characterize the physical environment in a space where radiant sources (like a heated ceiling) occur, the following physical terms are applied:

Mean Radiant Temperature ($\bar{t}_r$) - the uniform temperature of an enclosure in which an occupant would exchange the same amount of radiant heat as in the existing non-uniform environment.

Operative Temperature (t_o) - the uniform temperature of an enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the existing non-uniform environment.

Plane Radiant Temperature (t_{pr}) - the uniform temperature of an enclosure in which the irradiance on one side of a small plane element is the same as in the existing non-uniform environment.

Radiant Temperature Asymmetry (Δt_{pr}) - the difference between the plane radiant temperature of the two opposite sides of a small plane element.

The radiant temperature asymmetry is a new term introduced to describe the asymmetry of a radiant field. For heated ceilings it refers to a small horizontal element 0.6 m above the floor (the hight of the 'center' of a seated person). The vector radiant temperature introduced by McIntyre (4) is equal to the maximum radiant temperature asymmetry when the orientation of the plane element is varied.

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 one experiment ($3\frac{1}{2}$ h). All subjects were clothed in the KSU-standard uniform (5), which simulates a light clothing ensemble with a clo-value of 0.6, comprising a cotton twill shirt and trousers, cotton undershorts and cotton sweat socks. In addition, the subjects wore light open sandals (not part of the KSU-uniform).

All experiments took place in the morning or afternoon during the period Oct.-Dec. Anthropometric data for the subjects are listed in Table 1.

EXPERIMENTAL FACILITIES

The experiments took place in the environmental chamber at the Laboratory of Heating and Air Conditioning, Technical University of Denmark. In the chamber (dimensions 4.7 x 6.0 x 2.4 m), the supply air is uniformly distributed over the perforated floor and the air is exhausted through the lighting troffers and along the periphery of the ceiling. Although the air change is around 60 h^{-1}, the air velocity in the occupied zone is less than 0.1 m/s. A flow of air at room temperature behind the plastic sheet walls kept the walls at a temperature equal to, or slightly above the air temperature in the room. The floor temperature was equal to the air temperature. In the chamber, described in principle by Kjerulf-Jensen et al. (6), the air temperature and the humidity can be changed quickly and controlled accurately.

For application in the present experiments, a light ceiling (2.2 x 2.2 m) was suspended at a height of 2.0 m above the floor as shown in Fig. 1. The suspended ceiling consisted of 10 mm plywood insulated on both sides with approx. 25 mm rockwool. Underneath the suspended ceiling an electrically heated plastic foil was placed. A paint with an emittance estimated to be 0.95 was applied to the foil. By changing the voltage, the surface temperature of the suspended ceiling could be controlled.

The subject was seated under the center of the heated ceiling in a chair with a seat and a back composed of plastic strips, which had only a negligible effect on heat loss from the body. The angle factor between the seated person and the heated ceiling was calculated from Fanger's diagrams (7,8) to be 0.11. The angle factor between the person and the walls was 0.38 and the angle factor in relation to all other surfaces in the chamber (kept at air temperature) was thus 0.51.

PHYSIOLOGICAL MEASUREMENTS

The skin temperatures of each subject were measured by means of 14 thermistors taped to the skin by surgical tape. The 14 thermistors were distributed evenly over the body surface as shown in Fig. 2 (9). The rectal temperature was measured by a flexible thermistor rectal probe.

EXPERIMENTAL PROCEDURE

The experimental procedure was mainly the same as applied by Olesen et al. (10) in a similar study of radiant asymmetry from vertical surfaces. 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 h. The subject put on the 'thermistor harness', and the thermistors were taped to the skin. He put on the clothing and entered the chamber.

At the start of the experiment the air temperature (= the mean radiant temperature) was set at 25°C which was estimated to be the temperature which most likely would keep a seated person clothed at 0.6 clo thermally neutral.

Since it was important that the environment was kept thermally neutral for the subject, the ambient temperature was adjusted according to his requests. As in several earlier comfort studies (11,12,13,14), this was done by asking the subject every 5 min throughout the 3½-h experiment whether he would like the environment to be warmer, cooler, or the same, and then immediately altering the temperature according to his requests (Fig. 3).

During the first hour the ceiling was unheated. In the following five half-hour periods the subject was exposed to five different ceiling temperatures as indicated in Table 2. When the ceiling temperature was increased, the air temperature was lowered to provide an unchanged operative temperature, calculated to maintain thermal neutrality for the subject (see Table 2). During each half-hour period the voltage applied to the electrically heated ceiling was kept constant. This meant that any minor change of the air temperature requested by the subject provided an equal change of the ceiling and the mean radiant temperature.

Every 5 min during the entire experiment the subject was asked about local thermal sensation, discomfort and freshness of the air according to the procedure shown in Fig. 3.

All temperatures were automatically reqistered every 5 min by means of a data recording system outside the chamber. During the experiment the subject was kept occupied by reading, and was prohibited from eating or drinking while the test was in progress, although moderate smoking was allowed.

THERMAL MANIKIN

The thermal manikin developed by Madsen (15) has a shape which simulates approximately the body of a normal human being. It consists of a thin shell of fiberglass reinforced polyester. The manikin is divided into 16 sections, each being electrically heated internally. Thermostats control the internal temperature of each section at 36.5°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 a uniform environment at 25.3°C. The manikin was then exposed to the same five radiant temperature asymmetries (same voltage applied to electrical ceiling) as the subjects. In each of these conditions the air temperature was decreased until the total heat loss from the manikin was the same as in the uniform environment.

RESULTS

In the analysis of the physical, subjective, and physiological measurements, means were calculated of the final three observed values during each exposure, when approximate steady-state conditions were assumed. Means were thus calculated of the measurements taken 50, 55 and 60 min after the beginning of the initial period with a uniform environment, and of those taken 20, 25 and 30 min after the beginning of each of the following half-hour periods.

Neutral Temperatures

In Table 3, means as described above are listed of the air temperatures preferred by the 16 subjects during the six different radiant temperature asymmetries. No significant difference was found between males and females.

Also listed in Table 3 are the ceiling and wall temperatures, the mean radiant temperatures, and the operative temperatures. There was no significant difference between the operative temperatures in the six experimental cases, i.e. the air temperatures preferred by the subjects were such that constant operative temperatures were maintained. In Fig. 4, the observed preferred air temperatures are plotted against the mean radiant temperature. The regression line shows a slope not significantly different from the prediction given by Fanger's comfort equation (8), but shows a slightly higher relative influence of mean radiant temperature than found by McIntyre and Griffiths (16), McNall and Schlegel (17), and by Nielsen and Pedersen (18).

The preferred operative temperatures are in excellent agreement with the preferred temperatures found in the same chamber in other studies with a uniform thermal environment (14), but slightly lower than those found in the "old" environmental chamber at the Technical University of Denmark (13).

Local Sensation and Discomfort

During each half-hour period (one radiant condition) each subject was asked six times whether he felt warm or cool on any part of the body and whether he regarded this as uncomfortable. Only the last three responses (20, 25 and 30 min after the beginning of each condition) were considered in the analysis. At this time the subjects were close to neutrality for the body as a whole, and any transient discomfort due to the sudden change from one experimental condition to the next was assumed to have disappeared. It was decided to regard a radiation level as uncomfortable for a given subject if he indicated local discomfort at least twice (of three responses). An analogous criteria was used for local warm or cool sensation. At each radiation level the percentage of subjects who felt local discomfort and who experienced a local thermal sensation were calculated (see Table 4).

Local discomfort was felt either at the head (uncomfortably warm) or at the feet (uncomfortably cool) or at both places at the same time. Local warm or cool sensations were assigned to the same two regions of the human body.

In Table 4 the percentage of subjects indicating a local sensation or a local discomfort due to a warm head or cold feet are listed separately. It is remarkable that a sensation of cold on the feet was almost as frequent as a warm sensation on the head. Similarily, discomfort due to cold feet occurred almost as frequently as discomfort due to a warm head.

In Fig. 5, regression lines (based on a probit analysis) show the percentage of subjects indicating a local thermal sensation and local discomfort (on the head or the feet, or both combined) as a function of the radiation from the heated ceiling. The two regression lines are nearly parallel, i.e. local discomfort of the same percentage of subjects was experienced at a radiant temperature asymmetry which was about 8K higher than the asymmetry at which a local thermal sensation was experienced.

The regression line for discomfort intersects the ordinate axis at 3.5%, i.e. 3.5% are predicted to be uncomfortable when the thermal environment is completely uniform (unheated ceiling). With increasing ceiling temperature any increment in the percentage of those experiencing discomfort (above 3.5%) must have been caused by the thermal non-uniformity created by the radiant ceiling.

The curve in Fig. 6 shows the percentage of people feeling uncomfortable due to radiant asymmetry. The curve is calculated by subtracting 3.5% from the regression line in Fig. 5. The figure also shows Chrenko's curve (group B), which predicts a considerably higher percentage of persons in discomfort (1).

If it is accepted that no more than 5% feel uncomfortable, Fig. 6 shows that the radiant temperature asymmetry should be less than 4K.

Subjective mean votes concerning the freshness of the air were found to be close to neutral, and no significant influence of the radiation (or the air temperature) on the freshness of the air was found.

In all the subjective responses no significant difference was observed between males and females.

Physiological Measurements

In Table 5, mean values of the rectal and mean skin temperature are listed for the six experimental conditions. These remained constant, independent of the radiation. Although the mean skin temperature remained constant, there was an increasing difference between the local skin temperatures at the upper and lower parts of the body when the radiation increased. As suggested by Olesen and Fanger (9) these differences can be expressed by the non-uniformity of the skin temperature, defined as the standard deviation of the skin temperature measurements over the body surface. This non-uniformity, listed in Table 5, increased from 1.4K in the uniform thermal environment to 2.2K at the highest radiation level.

Fig. 7 shows the two skin temperatures at the head region (forehead and back of the neck) and the two skin temperatures at the foot region (instep and calf) as a function of the radiation level. It may be seen that the temperature of the back of the neck increased and the instep and calf temperatures decreased, while the forehead temperature remained constant during increasing radiation. The other ten skin temperatures changed less than 1K from the uniform thermal environment to the highest radiation level.

No significant differences were observed between the physiological measurements for males and females.

Measurements with the Thermal Manikin

In a uniform thermal environment at 25.3^{o}C the total heat loss from the manikin was measured at 50.2 W/m^2. The air temperatures required to maintain this total heat loss when the manikin was exposed to the same five levels of radiation as the subjects are listed in Table 6. For comparison, the corresponding decrements of the air temperature required to keep the subjects neutral are also listed. The decrements found in the subject experiments were somewhat lower than those found with the manikin.

Although the total heat loss from the manikin was constant, there was a considerable change in the heat loss from the upper and lower parts of the body. The heat losses from 16 different regions of the manikin were measured separately, but were combined to 9 regions, due to the right/left symmetry. The heat losses from these 9 regions of the manikin in a uniform environment at 25.3^{o}C are listed in Table 7, and the percentage changes of the heat losses from the different regions, when exposed to radiation, are shown in Fig. 8. The radiation decreased the heat loss from the arms and especially from the chest and the head, while the heat loss was increased from the back, the legs and the feet, due to the lower air temperature.

DISCUSSION

The most important result of the present study is the curve in Fig. 6 which predicts the percentage of people feeling uncomfortable due to overhead radiation.

Chrenko (1) reported the percentage of persons feeling uncomfortable due to overhead radiation, and his results are also shown in Fig. 6. Chrenko's curve predicts a considerably higher percentage of persons feeling uncomfortable, and the reason is presumably that he maintained a constant air temperature while increasing the temperature of the ceiling. The increment of the mean radiant temperature could have caused a sensation of warmth for the body as a whole. This might in itself have caused discomfort for some of his subjects, and others might have been more sensitive to overhead radiation due to the general sensation of warmth. In the present study, all subjects were kept thermally neutral. This would also be the aim in most cases in practice.

A fixation of a limit for acceptable overhead radiation 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. But it seems reasonable to accept only a minor increment in the number of persons feeling uncomfortable in ceiling-heated spaces, compared to spaces with no overhead radiation. 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 (8). A percentage of persons feeling uncomfortable due to overhead radiation of the same order of magnitude would presumably be acceptable in most cases in practice. A figure of 5% feeling uncomfortable due to overhead radiation is therefore suggested as the criteria for design calculation in spaces with high standards for the indoor climate. It is usual that design calculations are based on the design outdoor conditions in winter. During the major part of the heating season the temperature of the heated ceiling is lower than for the design case, and considerably fewer persons are then predicted to experience discomfort.

Five percent feeling uncomfortable corresponds to a radiant temperature asymmetry of 4K (see Fig. 6). For practical applications the corresponding allowable ceiling temperature can be found from Fig. 9 as a function of the angle factor to the ceiling.

The 4K limit of the radiant temperature asymmetry happens to agree well with the limit suggested by Chrenko ("elevated mean radiant temperature" = 2.2K) although he predicts more than 20% feeling uncomfortable at his limit (Fig. 6).

McNall and Biddison (2) exposed 16 subjects to a heated ceiling of 56°C while all other surfaces in the environmental chamber were kept at 16°C, and the mean radiant temperature was equal to the air temperature (26°C). This corresponds to a radiant temperature asymmetry of 4K. Of the subjects voting neutral, 21% were found to feel uncomfortable; this was not significantly different from the percentage that were feeling uncomfortable among a control group of 35 other subjects who were exposed to a uniform environment of 26°C. The reason for the high number voting uncomfortable among the control group is not known.

An objection to McNall and Biddison's experimental method is that they kept a constant air temperature in their experiments and balanced the hot ceiling by keeping cold walls. This is unrealistic since in practice, the air temperature is usually lowered when a heated ceiling is in use.

Griffiths and McIntyre (3) exposed 24 subjects to a control condition and to three different ceiling temperatures (Table 8). The vector radiant temperature (1.0 m above the floor) was in the four cases between 4 and 12K. The authors found no significant difference between the discomfort experienced by the subjects when they were exposed to the four conditions. They recommended that the vrt should be kept lower than 20K. But a reanalysis (Table 8) shows that the subjects were exposed to a radiant non-uniformity that did not vary nearly as much as intended during the four conditions (the radiant temperature asymmetry varied only between 5 and 7K). Furthermore, the experimental chamber was cooler (the operative temperature was 0.9-1.8K lower) when the subjects were exposed to the two highest ceiling temperatures than during the control condition. This may explain why Griffiths and McIntyre were unable to detect any significant differences between the discomfort experienced by their subjects in the four conditions.

Griffiths and McIntyre had aimed at providing an equal thermal sensation in the four conditions and were therefore surprised that the subjects felt cooler in condition 4 (hot ceiling). The authors suggest than man might be less thermally sensitive to vertical radiation than to radiation from other directions. But there seems to be a more obvious explanation of their observation: The subjects were exposed to an operative temperature which was lower in condition 4 than in the other three conditions (Table 8).

Olesen et al. (11) studied the effects of lateral asymmetry. The nude subject sat in the center of an environmental chamber which was maintained at his preferred temperature. The temperature of a side wall was then raised by 5K and that of the opposite wall was reduced by 5K, so the mean radiant temperature remained equal to the air temperature. These temperature changes in 5K increments were made each half hour until the temperature difference between the walls reached 20K. Each of the 16 subjects were questionned about sensation and discomfort in the same way as in the present study. Accepting 5% feeling uncomfortable, a limit of the radiant asymmetry equal to 10K was found for nude subjects. Based on theoretical calculations a formula was suggested to estimate the corresponding limits for clothed persons. These limits are much higher than the limit determined in the present study, which indicates that man is more sensitive to vertical than to horizontal (asymmetric) radiation. The experimental conditions in the studies of Olesen et al (11) were, however, somewhat unrealistic: The subjects were nude, preferring an air temperature of 28-29°C, and the mrt was maintained constant by decreasing and increasing the temperature of the opposite walls. Further research is recommended on radiant discomfort due to vertical surfaces, studying normally clothed subjects exposed to radiation from warm and cold surfaces in separate experiments.

An interesting observation in the present study is that subjects who felt uncomfortable, when exposed to overhead radiation, attributed their discomfort not only to a warm head but nearly equally frequently to cold feet (Table 4). This corresponds well with the increased skin temperature at the head region and the decreased skin temperature at the foot region when the subjects were exposed to increasing overhead radiation (see Fig. 7). However, it should be noted that the skin temperature of the forehead did not increase, presumably because the faces of reading subjects inclined downwards and therefore were only partly exposed to radiation from the ceiling. The non-uniformity of the skin temperature over the body surface (= the standard deviation) was found to be 1.4K in a uniform environment and this agrees well with the results of Olesen and Fanger (9). At the highest radiation the non-uniformity was 2.2K (Table 5). It is predicted that 50% of the population experiences a local thermal sensation when the non-uniformity of the skin temperature is increased from 1.4 to 1.7K.

The decreased heat loss from the upper part of the body (due to overhead radiation) and the increased heat loss from the lower parts of the body (due to lower air temperature) are confirmed by the manikin measurements (Fig. 8).

Another interesting observation is that the preferred mean skin temperature (and the rectal temperature) was remarkably constant, independent of the radiation from the ceiling (Table 3). This confirms earlier findings that man feels thermally neutral at a certain skin temperature independent of the combination of the environmental variables (8,11,19).

The mean radiant temperature was found to influence the thermal manikin more than the subjects (Table 6), and the reason for this is probably that the trunk of the manikin leaned slightly backwards and that the legs were half outstretched, while the subjects occasionally leaned forward, crossed their legs, or kept their feet under the chair. This increased the irradiation area of the manikin compared to the subjects.

The mean radiant temperature and the air temperature had approximately an equal influence on the thermal sensation of the subjects (Fig. 4). This agrees well with the ASHRAE Comfort Standard (20) and with the prediction of Fanger's comfort equation (8), while the observed influence of the mean radiant temperature was slightly higher than found by McNall and Schlegel (17), McIntyre and Griffiths (16) and by Nielsen and Pedersen (18).

The subjective sensation of freshness of the air was not increased with increasing radiation and decreasing air temperature. This is in agreement with radiation studies by McIntyre and Griffiths (16), while other studies, not involving radiation (21,22) have indicated increased subjective freshness when the air temperature was decreased. The irradiation on the head may have counteracted the positive effect of the cooler air.

CONCLUSIONS

1. A curve (Fig. 6) has been established, showing the percentage of people feeling discomfort due to overhead radiation, as a function of the radiant temperature asymmetry. The curve applies for sedentary people who feel thermally neutral for the body as a whole.

2. It is recommended that a heated ceiling should not provide a radiant temperature asymmetry exceeding 4K in spaces with high standards for the indoor climate. Less than 5% of the population are then predicted to feel uncomfortable due to overhead radiation. The corresponding limit for the ceiling temperature can be found from Fig. 9 for different sizes and heights of the heated ceiling.

3. Increasing discomfort due to increasing overhead radiation with lowered air temperature, can be attributed to warmer head and colder feet.

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Table 1. Anthropometric Data for the Subjects

	No. of Subjects	Age Years	Height m	Weight kg	DuBois Area m^2
Females	8	21 ±1+	1.70 ±.06	61.8 ±7.3	1.7 ±.1
Males	8	23 ±2	1.80 ±.09	77.1 ±17.4	2.0 ±.2
Females and Males	16	22 ±2	1.75 ±.09	69.5 ±15.1	1.8 ±.2

+ standard deviation of the sample.

Table 2. Experimental Plan

Time min	Difference Between Ceiling and Air Temp. K	Difference Between Operative and Air Temp. K
0 - 60	0	0
60 - 90	10	0.6
90 - 120	20	1.3
120 - 150	30	2.1
150 - 180	42	3.1
180 - 210	48	3.6

Table 3. Mean values of the air temperatures preferred by the 16 subjects and the corresponding mean values of the ceiling temperature, the wall temperatures, the mean radiant temperature, and the operative temperature, during the six radiant temperature asymmetries.

Radiant Temp. Asymmetry K	Preferred Air Temp. °C	Ceiling Temp. °C	Mean Wall Temp. °C	Mean Radiant Temp. °C	Operative Temp. °C
0	24.1 ±1.6+	24.1	24.1	24.1	24.1
4.5	24.0 ±1.5	34	24.2	25.2	24.6
9.2	23.0 ±1.7	43	23.4	25.7	24.3
14.1	22.3 ±1.3	52	22.9	26.4	24.3
20.4	21.4 ±1.1	63	22.2	27.2	24.2
23.6	20.6 ±1.5	69	21.5	27.5	24.0

+Standard deviation of the sample.

Table 4. Percentage of subjects who experienced a local thermal sensation or discomfort

Radiant Temp. Asymmetry	Local Sensation			Local Discomfort		
	Head	Feet	Total	Head	Feet	Total
K	%	%	%	%	%	%
4.5	12.5	12.5	25.0	0	6.3	6.3
9.2	37.5	31.3	56.3	12.5	12.5	25.0
14.1	56.3	43.8	81.3	25.0	37.5	43.8
20.4	75.0	62.5	93.8	56.3	50.0	75.0
23.6	81.3	62.5	87.5	62.5	43.8	68.8

Table 5. Physiological Measurements

Radiant Temp. Asymmetry	Rectal Temp.	Mean Skin Temp.	Non-uniformity
K	°C	°C	K
0	36.8 ±.5+	33.6 ±.5	1.4 ±.3
4.5	36.9 ±.5	33.5 ±.7	1.5 ±.4
9.2	36.8 ±.5	33.5 ±.7	1.7 ±.4
14.1	36.8 ±.5	33.5 ±.7	1.9 ±.4
20.4	36.8 ±.6	33.5 ±.7	2.0 ±.4
23.6	36.8 ±.6	33.5 ±.8	2.2 ±.4

+Standard deviation of the sample.

Table 6. Necessary decrement of air temperature to maintain an approximately constant total heat loss from the manikin

Radiant Temp. Asymmetry	Manikin		Decrement of Air Temp.	
	Heat Loss	Air Temp.	Manikin	Subjects
K	W/m^2	°C	K	K
0	50.2	25.3	0	0
4.5	50.4	24.4	0.9	0.1
9.2	50.0	23.3	2.0	1.1
14.1	49.8	22.2	3.1	1.8
20.4	50.6	20.8	4.5	2.7
23.6	50.3	20.4	4.9	3.5

Table 7. Heat loss from nine regions of the manikin exposed to a uniform thermal environment at 25.3°C

Part of Manikin	Head	Back	Chest and Abdomen	Upper Arms	Lower Arms	Hands	Thighs	Lower Legs	Feet	Total
Percentage of Total Area	10	12	15	9	7	6	18	16	7	100
Heat Loss W/m^2	50.7	45.9	32.8	48.3	57.9	56.3	58.1	49.5	51.4	50.2

Table 8. Experimental conditions in tests by Griffiths and McIntyre (3), where 24 subjects (low seats) were exposed to radiation from a heated ceiling. Dimension of environmental chamber: 3.7 x 3.7 x 2.4 m.

		Condition Number			
		1	2	3	4
Ceiling Temp.	°C	26.5	30.0	38.0	45.0
Wall Temp.	°C	26.5	25.5	20.5	15.0
Floor Temp.	°C	20.2	20.4	20.7	22.3
Air Temp.	°C	21.0	21.0	21.0	21.0
Mean Radiant Temp.	°C	24.8	24.7	22.9	21.2
Operative Temp.	°C	22.9	22.9	22.0	21.1
Vector Radiant Temp. (1.0 m)	K	4.0	5.6	9.2	11.6
Radiant Temp. Asymmetry	K	5.1	6.1	7.3	6.9

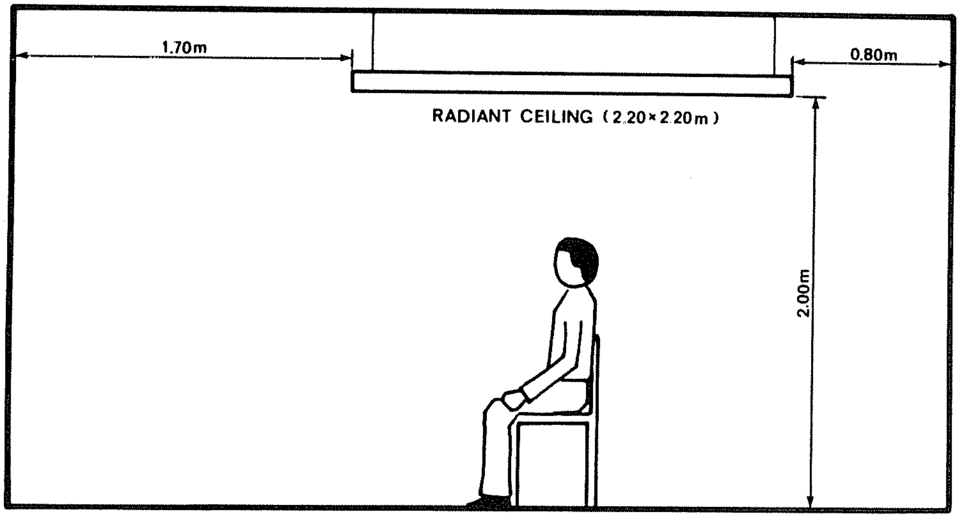

Fig. 1 Experimental set-up in the environmental chamber

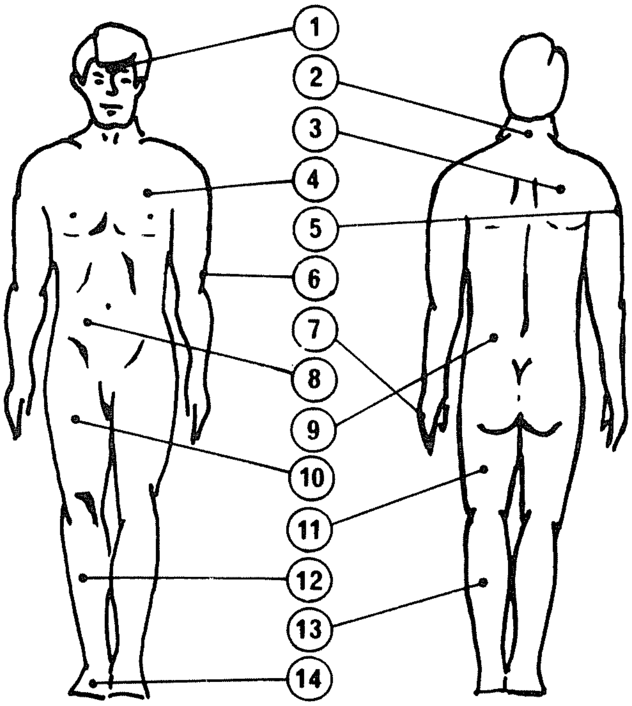

Fig. 2 Positions of the skin temperature sensors on the human body

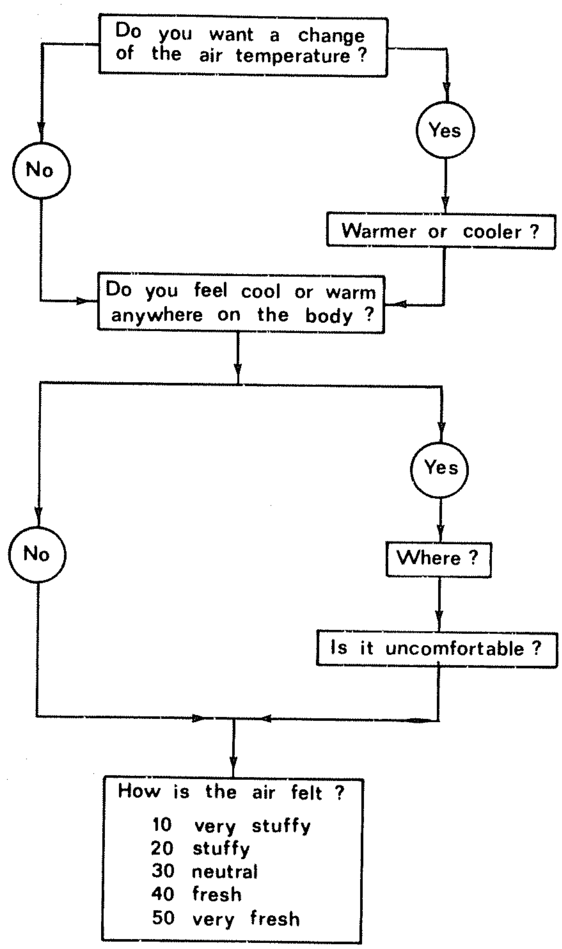

Fig. 3 Procedure for asking the subjects on thermal preference, local thermal sensation, discomfort and freshness of the air

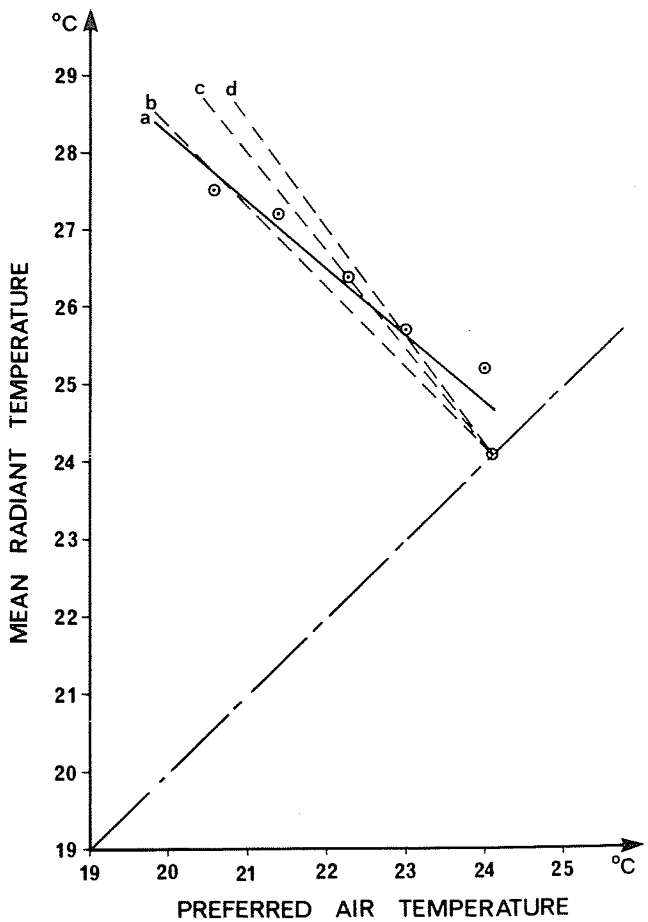

Fig. 4 The plotted points and the corresponding regression line, a, represents combinations of mean radiant temperature and air temperature preferred by the subjects (mean values). Through the preferred temperature without radiation (mrt = air temp. = 24.1°C) lines of constant thermal sensation are shown. Line b: predicted by Fanger's comfort equation (8); line c: McIntyre and Griffiths (16); line d: McNall and Schlegel (17) and Nielsen and Pedersen (18)

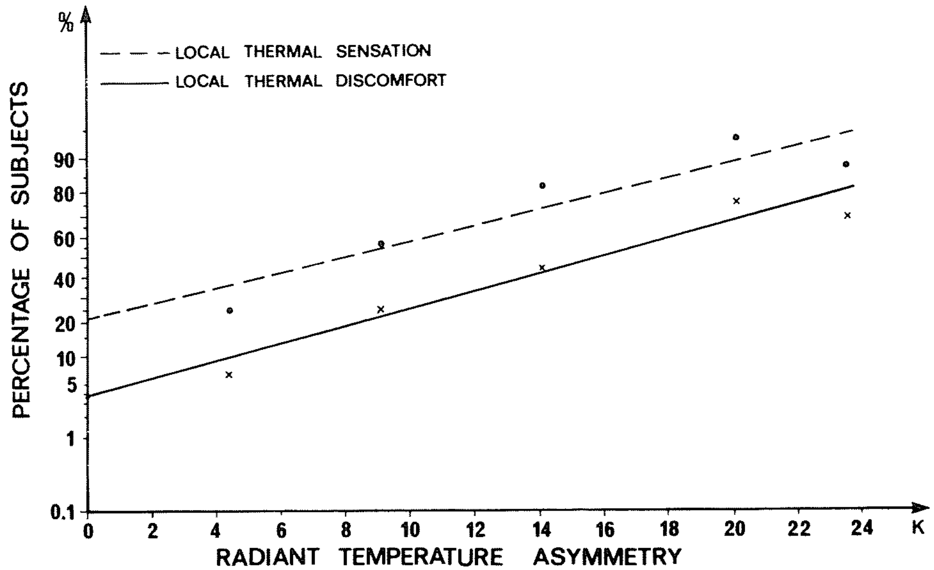

Fig. 5 Probit analysis of the subjective responses concerning local thermal sensation and thermal discomfort

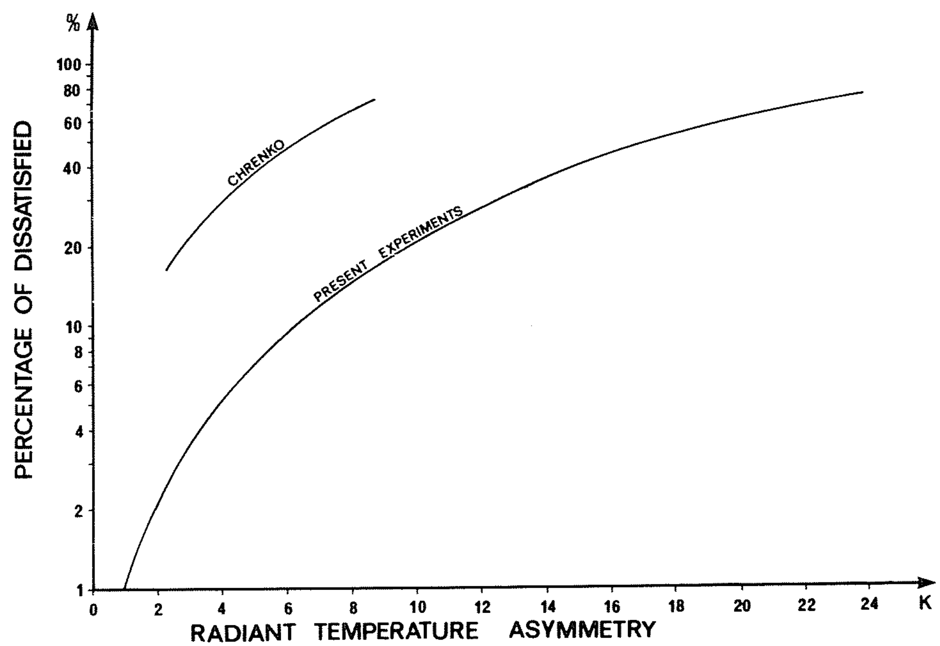

Fig. 6 Percentage of people expressing discomfort due to overhead radiation as a function of the radiant non-uniformity expressed by the radiant temperature asymmetry. The corresponding curve by Chrenko (group B) is shown for comparison.

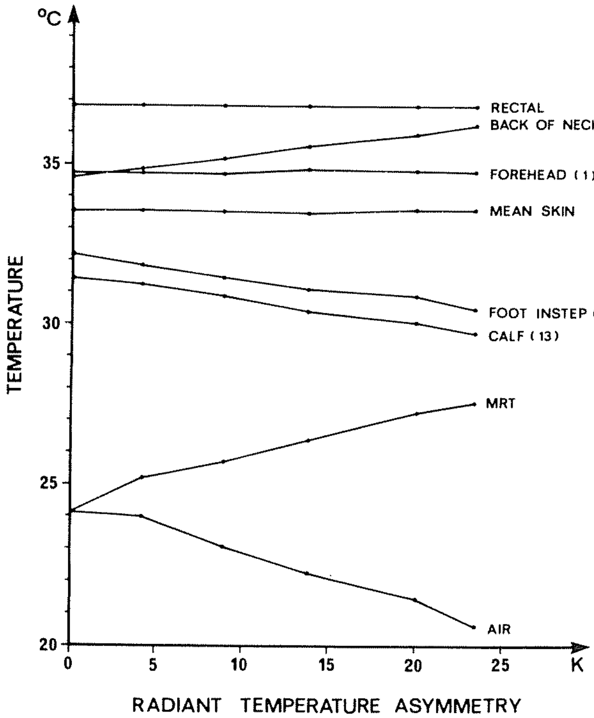

Fig. 7 Rectal and skin temperatures as a function of the radiant temperature asymmetry. The figures in parentheses refer to the positions of the skin sensors shown in Fig. 2

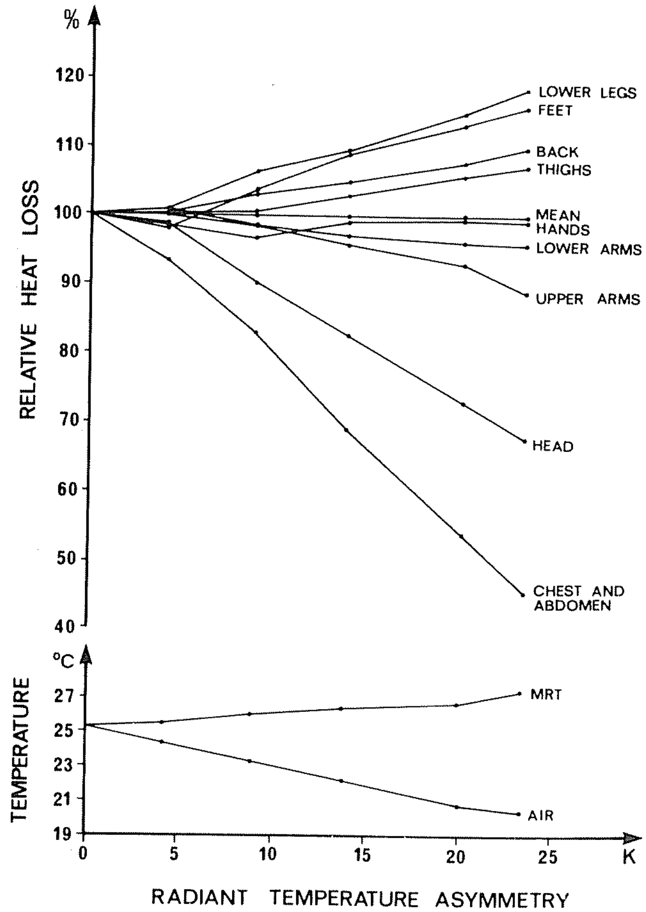

Fig. 8 The percentual change of the heat loss from the different sections of the thermal manikin, when exposed to overhead radiation

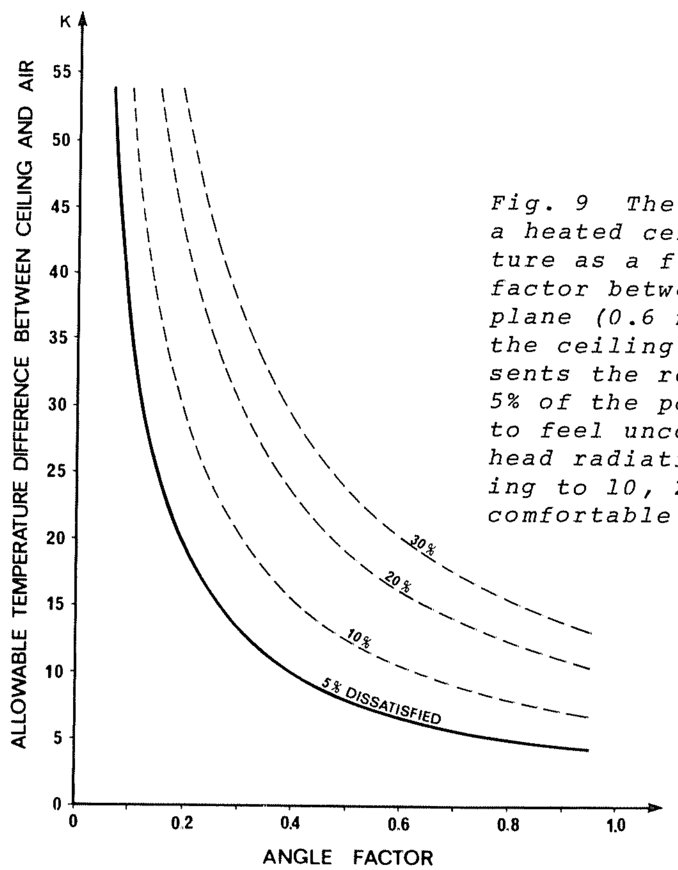

Fig. 9 The allowable temperature of a heated ceiling above air temperature as a function of the angle factor between a small horizontal plane (0.6 m above the floor) and the ceiling. The full line represents the recommended limit where 5% of the population are predicted to feel uncomfortable due to overhead radiation. Lines corresponding to 10, 20 and 30% feeling uncomfortable are shown dotted.

DISCUSSION

GEITEL WINAKOR, Prof., Iowa State Univ., Ames, IA: When you asked people if they were comfortable, did you use a numerical scale or just "yes-no"?

P.O. FANGER: We just asked the subjects whether they felt uncomfortable (see the procedure in Fig. 3). In some earlier studies, different kinds of psycho-physical scales have been applied to describe local discomfort. In the analysis you then have the problem of deciding where on the scale the discomfort limit should be situated. Instead we decided to ask the subjects directly by posing the above mentioned question.

MASHURI WARREN, Staff Scientist, LBL, Berkeley, CA: Have you looked at the effects of higher levels of clothing on your results?

FANGER: We have not studied this experimentally. At heavier clothing, the preferred air temperature will be lower. Under these circumstances warm dis-comfort at the head is less likely since the cool air may counteract the radia-tion from the heated ceiling. On the other hand, the cooler air would tend to create more complaints caused by cold feet.

We believe that the results of the present investigation can be applied with reasonable approximation for most typical indoor winter clothing ensembles.