Comfort Limits for Asymmetric Thermal Radiation

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SUMMARY

Groups of 32 and 16 subjects of both sexes were exposed in an environmental chamber to radiant asymmetry caused by a cool wall, a warm wall, and a cool ceiling. Each subject was tested individually while seated and clothed at 0.6 clo. During each 3.5-hour experiment the subject was exposed to six radiant temperature asymmetries. He was asked whether and where he experienced any local cool or warm sensation, and whether it was felt to be uncomfortable. During the entire experiment he was kept thermally neutral by changing the air temperature according to his wishes.

For cool walls, warm walls, and cool ceilings curves have been established showing the percentage of dissatisfied subjects as a function of the radiant asymmetry. Radiant asymmetry at a warm wall caused less discomfort than at a cool wall. A cool ceiling caused less discomfort than a warm ceiling. Accepting that 5% of the subjects may feel uncomfortable, a radiant temperature asymmetry of 10 °C is allowable at a cool wall, 23 °C at a warm wall, and 14 °C under a cool ceiling. A previous study showed that 4 °C is allowable under a warm ceiling. Radiant asymmetry had no significant impact on the operative temperatures preferred by the subjects. No significant differences were observed between the responses of men and women exposed to radiant asymmetry.

INTRODUCTION

Energy is used in buildings to provide thermal comfort for the occupants and to rationalize this purpose it is useful to identify man's comfort requirements.

The purpose of the present study is to determine the limits of asymmetric radiation to which man 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 but this condition is not always sufficient. A further requirement is that no local warm or cool discomfort is experienced on any part of the body; asymmetric radiation may create such local discomfort.

In an earlier study [1] we have investigated the comfort limits for asymmetric radiation from heated ceilings. The present study comprises similar investigations on asymmetric radiation from a cool or warm wall (or window) and from a cool ceiling.

McNall and Biddison [2] have earlier studied these cases but in the results it is difficult to separate local discomfort from general warm or cool discomfort for the body as a whole. Olesen et al. [3] studied the effect of radiant asymmetry from cool or warm walls for nude subjects.

In the present study subjects were studied in normal indoor clothing, and to separate local from general discomfort each subject was kept thermally neutral throughout each experiment.

RADIANT TERMS

To characterize the physical environment in a space where radiant sources 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

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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 term introduced by Fanger et al. [1] to describe the asymmetry of a radiant field. It refers to a small plane element 0.6 m above the floor (the height of the 'centre' of a seated person). The small plane element should be horizontal to characterize radiant asymmetry caused by a warm or cool ceiling. For radiant asymmetry caused by a warm or cool vertical surface, the small element should be vertical and parallel to the surface. 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

Thirty-two college-age persons (sixteen females and sixteen males) were used as subjects in the cool wall experiments. Sixteen college-age persons (eight females and eight males) were used as subjects in the warm wall and the cool ceiling experiments. Only persons in good health were allowed to participate. All subjects were volunteers who were paid for participating in the experiments. 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 sweatsocks. 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 winter and spring period. 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 $4.7 \times 6.0 \times 2.4$ m^3), 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. The temperatures of the walls and the floor were close to the air temperature in the room. 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.

To simulate the radiant asymmetry caused by a cool or warm wall, a vertical panel was

TABLE 1

Anthropometric data for the subjects

Experiment	Sex	No. of subjects	Age (yr)	Height (m)	Weight (kg)	DuBois area (m^2)
Cool wall	Females	16	22.1 ± 1.2*	1.69 ± 0.05	60.8 ± 6.9	1.70 ± 0.10
	Males	16	20.7 ± 1.8	1.83 ± 0.06	71.3 ± 5.8	1.92 ± 0.10
	Females and males	32	21.4 ± 1.7	1.76 ± 0.08	66.0 ± 8.2	1.81 ± 0.15
Warm wall and cool ceiling	Females	8	21.6 ± 0.7	1.71 ± 0.05	60.1 ± 6.9	1.70 ± 0.11
	Males	8	21.8 ± 1.4	1.82 ± 0.07	74.4 ± 7.1	1.96 ± 0.13
	Females and males	16	21.7 ± 1.1	1.77 ± 0.08	67.3 ± 10.0	1.83 ± 0.17

*Standard deviation of the sample.

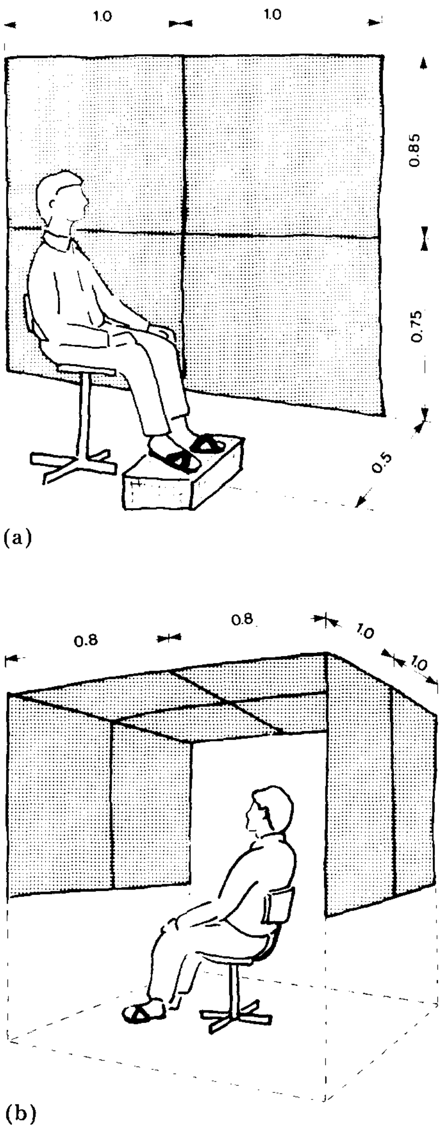

Fig. 1. Experimental set-up in the environmental chamber. The top illustration shows a subject at the vertical panel simulating the cool or warm wall. His 'centre' is 0.5 m from the panel centre. The bottom illustration shows a subject under the cool ceiling panels.

set up in the chamber. The panel consisted of four water-filled panel radiators painted black with a paint having an emittance greater than 0.95. Some part along the periphery of each panel radiator was unheated/uncooled. The back of the panel was insulated with 150 mm polyurethane foam. The water temperature of the hydronic system could be controlled to maintain any surface temperature of the panel between 0 °C and 70 °C.

The subject was seated with his side to the panel as shown in Fig. 1. The angle factor to the cool or warm part of the panel was estimated to be 0.25. The position is common in practice, for instance for people working in offices with large windows. Olesen et al. [3] found that no other positions of the body in relation to vertical surfaces caused higher asymmetry discomfort.

To simulate the radiant asymmetry caused by a cool ceiling, the same panel as described above was situated horizontally above the subject, 180 cm above the floor. To increase the angle factor from the subject, two extra vertical panels were placed as shown in Fig. 1. This set-up simulated a much larger cool ceiling. The angle factor to the cool part of the ceiling was estimated to be 0.20.

During each experiment the subject was seated in a chair, which had only a negligible effect on the heat loss from the body.

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 [7]. The rectal temperature was measured at 8 cm depth by a flexible thermistor probe.

EXPERIMENTAL PROCEDURE

The experimental procedure was the same as applied by Fanger et al. [1] in a similar

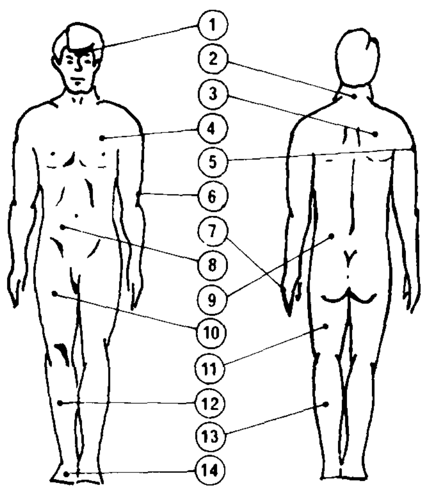

Fig. 2. Positions of the skin temperature sensors on the human body.

study of radiant asymmetry from heated ceilings. Each subject reported in good time prior to the commencement of the experiment. It was ascertained that he/she had sufficient sleep during the previous night and had no fever. The subject put on the thermistor harness, and the thermistors were taped to the skin. He/she put on the clothing and entered the chamber.

At the start of the experiment the air temperature (= the mean radiant temperature) was set at 24 °C. This was estimated to be the temperature which most likely would keep a seated person clothed at 0.6 clo thermally neutral at the beginning of an experiment. During the experiment the vapor pressure was kept constant at 1 kPa.

Since it was important that the environment be kept thermally neutral for the subject, the ambient temperature was adjusted according to his/her requests. As in several earlier comfort studies [1, 3, 8, 9], this was done by asking the subject every 5 min throughout the 3.5-h experiment whether he/she would like the environment to be warmer, cooler, or the same, and then immediately altering the temperature according to his/her request (Fig. 3). At each requested change, the air temperature and panel temperatures were both changed by 1 °C during the first 30 min and by 0.5 °C during the last 180 min of the experiment.

During the first hour the panel temperature was maintained equal to the air temperature. In the following five half-hour periods the subject was exposed to five radiant asymmetries. This was done by changing the temperature of the panel in steps as shown in Table 2. At the same time the air temperature was changed as shown in Table 2 to maintain the same operative temperature as before the change of radiant asymmetry.

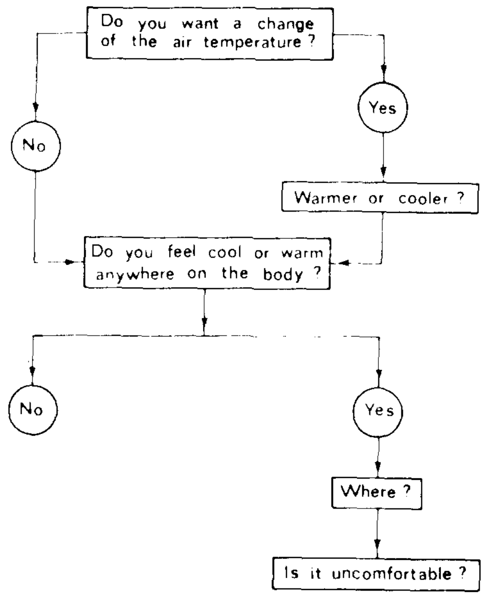

Fig. 3. Procedure for asking the subjects about their thermal preference, local thermal sensation and discomfort.

Every 5 min during the entire experiment, the subject was asked about local thermal sensation and discomfort according to the procedure shown in Fig. 3. All temperatures were automatically registered 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.

TABLE 2

Experimental plan

		Step change (°C) at					
		0 min	60 min	90 min	120 min	150 min	180 min
Cool wall	Panel temp.	0	−7	−5	−5	−5	—
	Air temp.	0	+1.2	+0.7	+0.7	+0.7	—
Warm wall	Panel temp.	0	+9	+9	+9	+9	+9
	Air temp.	0	−1.6	−1.7	−1.8	−2.0	−2.2
Cool ceiling	Panel temp.	0	−7	−5	−5	−5	—
	Air temp.	0	+1.0	+0.7	+0.6	+0.6	—

THERMAL MANIKIN

A thermal manikin [10] was used to determine the operative temperature. The thermal manikin has a shape which simulates approximately the body of a normal human being, and it consists of a thin shell of fiberglass-reinforced polyester. The manikin is divided into 16 sections, each being electrically heated. Thermostats control the internal temperature of each section at 36.5 °C. The heat loss, equal to the energy supply, was measured for each of the 16 sections.

The manikin, clothed in the 0.6 clo standard uniform, was seated in the same type of chair as the subjects and exposed to the same conditions as the subjects. This means that the manikin was exposed to a thermally uniform environment and to the same radiant temperature asymmetries as were the subjects. The air temperature was maintained at the mean of the air temperatures preferred by the subjects. From the total heat loss the operative temperature could be determined, and the heat loss from each section of the manikin provided information on the local impact of the environment. The manikin was removed while the radiant temperature asymmetry was measured by the Brüel & Kjaer Indoor Climate Analyser, Type 1213 with the sensor situated at the 'centre' of the subject. At the same time the mean air velocity and the standard deviation were measured at head, centre and ankle level by the same instrument.

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 Tables 3 - 5, means as described above are listed of the air temperatures preferred by the subjects during the six different radiant asymmetries. Also listed are the mean values of the corresponding panel temperatures, the operative temperatures measured by the thermal manikin, as well as the measured radiant temperature asymmetries. The mean radiant temperature was estimated from the air and operative temperatures, assuming the operative temperature to be the average of air and mean radiant temperatures. Furthermore Table 5 comprises measurements of the air velocity and its standard deviation during the cool ceiling experiment.

In Fig. 4, the preferred operative temperature is shown as a function of the radiant temperature asymmetry. The operative temperature was constant during the warm wall experiment as it was in the previous

TABLE 3

Cool wall: mean values and standard deviations of the measured preferred air temperature and panel temperature during the subject experiments. The corresponding value of operative temperature and radiant temperature asymmetry were measured during separate experiments

Period	Air temp. (°C)	Panel temp. (°C)	Mean radiant temp. (°C)	Operative temp. measured by manikin (°C)	Radiant temp. asymmetry (°C)
1	24.3 ± 1.5*	24.1 ± 1.5	24.1	24.2	0.4
2	25.9 ± 1.5	17.8 ± 1.5	23.7	24.8	5.3
3	27.1 ± 1.5	13.3 ± 1.5	22.9	25.0	8.6
4	28.1 ± 1.5	8.7 ± 1.5	22.3	25.2	12.8
5	29.0 ± 1.7	4.1 ± 1.7	21.4	25.2	16.6
6	29.6 ± 1.8	0.4 ± 0.5	21.4	25.5	18.2

*Standard deviation.

TABLE 4

Warm wall: mean values and standard deviations of the measured preferred air temperature and panel temperature during the subject experiments. The corresponding values of operative temperature and radiant temperature asymmetry were measured during separate experiments

Period	Air temp. (°C)	Panel temp. (°C)	Mean radiant temp. (°C)	Operative temp. measured by manikin (°C)	Radiant temp. asymmetry (°C)
1	23.1 ± 2.0*	23.2 ± 2.0	23.2	23.4	−0.2
2	21.9 ± 1.9	32.6 ± 2.0	25.3	23.6	6.6
3	20.7 ± 1.9	42.0 ± 1.9	26.5	23.6	13.3
4	19.3 ± 1.6	51.6 ± 1.6	27.5	23.4	20.7
5	17.9 ± 1.8	61.1 ± 1.8	29.3	23.6	28.0
6	16.7 ± 1.8	70.1 ± 3.3	30.5	23.6	35.1

*Standard deviation.

TABLE 5

Cool ceiling: Mean values and standard deviations of the measured preferred air temperature and panel temperature during the subject experiments. The corresponding values of operative temperature, radiant temperature asymmetry and air velocity were measured during separate experiments.

Period	Air temp. (°C)	Panel temp. (°C)	Mean radiant temp. (°C)	Operative temp. measured by manikin (°C)	Radiant temp. asymmetry (°C)	Air velocity at 1.1, 0.6, 0.1 m height (m/s)
1	22.7 ± 1.9*	22.7 ± 1.9	22.7	22.7	0	0.04 ± 0.03 0.08 ± 0.04 0.08 ± 0.07
2	24.1 ± 2.3	16.0 ± 2.3	19.9	22.0	4.4	0.09 ± 0.05 0.13 ± 0.10 0.13 ± 0.08
3	25.8 ± 2.6	12.1 ± 2.6	19.0	22.4	7.5	0.13 ± 0.07 0.12 ± 0.06 0.12 ± 0.05
4	27.2 ± 2.2	7.9 ± 2.2	18.6	22.9	10.5	0.13 ± 0.06 0.14 ± 0.07 0.15 ± 0.08
5	28.7 ± 1.6	3.9 ± 1.5	18.1	23.4	13.0	0.17 ± 0.09 0.18 ± 0.09 0.18 ± 0.07
6	29.7 ± 1.9	0.8 ± 0.3	17.5	23.6	15.0	0.20 ± 0.11 0.20 ± 0.10 0.20 ± 0.10

*Standard deviation.

warm ceiling study [1]; but it increased slightly during the cool wall and cool ceiling experiments. The 32 subjects in the cool wall experiments preferred temperatures around 1.5 °C higher than the 16 subjects in the warm wall and cool ceiling experiments.

Local sensation and discomfort

During each half-hour period (one radiant asymmetry), each subject was asked six times whether he/she felt warm or cool on any part of the body and whether he/she 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 radiant asymmetry to the next was assumed to have disappeared.

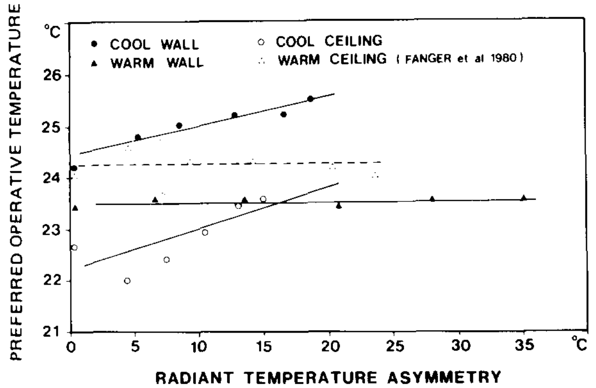

Fig. 4. Preferred operative temperature as a function of radiant temperature asymmetry during the experiments with cool wall, warm wall and cool ceiling.

It was decided to regard a radiant asymmetry as uncomfortable for a given subject if he/she indicated local discomfort at least twice (of three responses). An analogous criterion was used for local warm or cool sensations. At each asymmetry level the percentage of subjects who felt local discomfort and who experienced a local thermal sensation was calculated (see Tables 6 - 8). In the Tables it is furthermore indicated where the discomfort was experienced.

In Figs. 5 - 7, regression lines (based on a probit analysis) show the percentage of subjects indicating a local thermal sensation and local discomfort as a function of the radiant asymmetry.

TABLE 6

Cool wall: percentage of subjects who experienced a local thermal sensation or discomfort

Cool wall		Radiant temperature asymmetry (°C)				
		5.3	8.6	12.8	16.6	18.2
Sensation (%)	total	46.9	65.6	81.3	75.0	84.4
Discomfort (%)	left	3.1	0.0	9.4	28.1	37.5
	right	0.0	0.0	0.0	0.0	9.3
	total	3.1	0.0	9.4	28.1	43.8

TABLE 7

Warm wall: percentage of subjects who experienced a local thermal sensation or discomfort

Warm wall		Radiant temperature asymmetry (°C)				
		6.6	13.3	20.7	28.0	35.1
Sensation (%)	total	50.0	75.0	87.5	87.5	93.8
Discomfort (%)	left	0.0	0.0	6.3	6.3	6.3
	right	0.0	6.3	6.3	0.0	6.3
	total	0.0	6.3	12.5	6.3	12.5

TABLE 8

Cool ceiling: percentage of subjects who experienced a local thermal sensation or discomfort

Cool ceiling		Radiant temperature asymmetry (°C)				
		4.4	7.5	10.5	13.0	15.0
Sensation (%)	total	56.3	75.0	75.0	75.0	62.5
Discomfort (%)	head + neck	0.0	0.0	0.0	6.3	6.3
	feet + ankles	0.0	0.0	0.0	0.0	0.0
	total	0.0	0.0	0.0	6.3	6.3

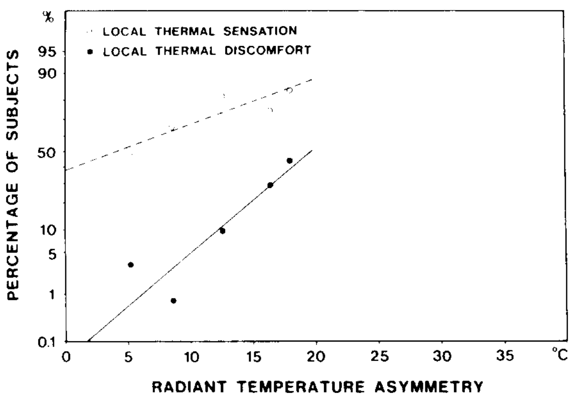

Fig. 5. *Cool wall:* probit analysis of the subjective responses concerning local thermal sensation and thermal discomfort.

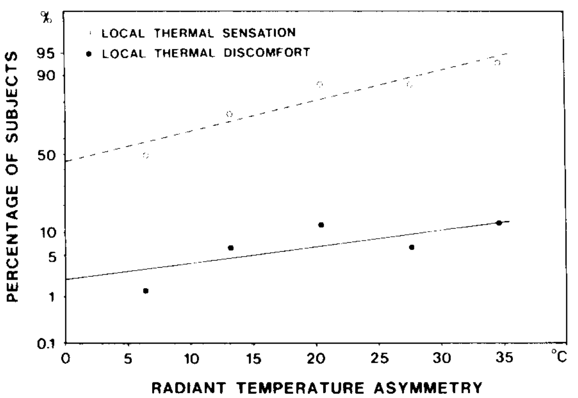

Fig. 6. *Warm wall:* probit analysis of the subjective responses concerning local thermal sensation and thermal discomfort.

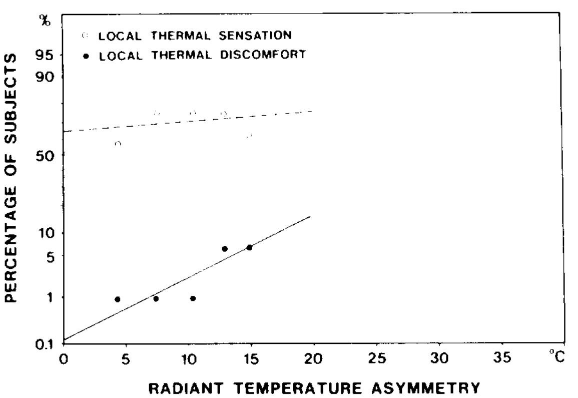

Fig. 7. *Cool ceiling:* probit analysis of the subjective responses concerning local thermal sensation and thermal discomfort.

It is obvious that most of the subjects experienced a local cool or warm sensation during the experiments. But few of them regarded this as uncomfortable. In Fig. 8

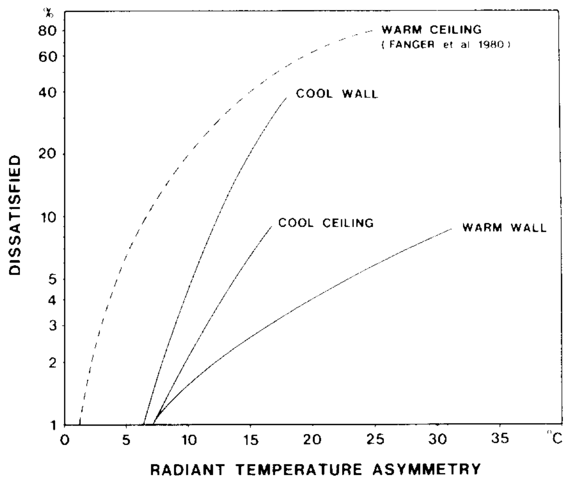

Fig. 8. Percentage of people expressing discomfort due to asymmetric radiation to a cool wall, warm wall or cool ceiling as a function of the radiant temperature asymmetry. For comparison, the corresponding curve is shown for a warm ceiling, obtained in an earlier study by Fanger et al. [1].

the percentage of dissatisfied subjects is shown for all three investigated cases as a function of the radiant asymmetry. For comparison the curve for warm ceilings is shown from our earlier study [1].

For the warm wall the curve in Fig. 8 is slightly different from the regression line in Fig. 6. The reason is that the regression line predicts 3% being uncomfortable even in a thermally uniform environment. This cannot be caused by radiant asymmetry, and 3% has therefore been subtracted from the regression line to obtain the curve of dissatisfied people in Fig. 8.

It is obvious from Fig. 8 that radiant asymmetry caused by a warm ceiling was felt to be the most uncomfortable while the cool wall was second, in producing discomfort. The cool ceiling and the warm wall only caused few complaints, and the curves for these cases are therefore based on a weak data basis.

In the ISO standard on thermal comfort [11], there is a recommendation to accept 5% feeling uncomfortable owing to radiant asymmetry. A 5% limit in Fig. 8 corresponds to a radiant temperature asymmetry of 4 °C for the warm ceiling, 10 °C for the cool wall, 14 °C for the cool ceiling, and 23 °C for the warm wall.

In all the subjective responses no significant differences were observed between females and males.

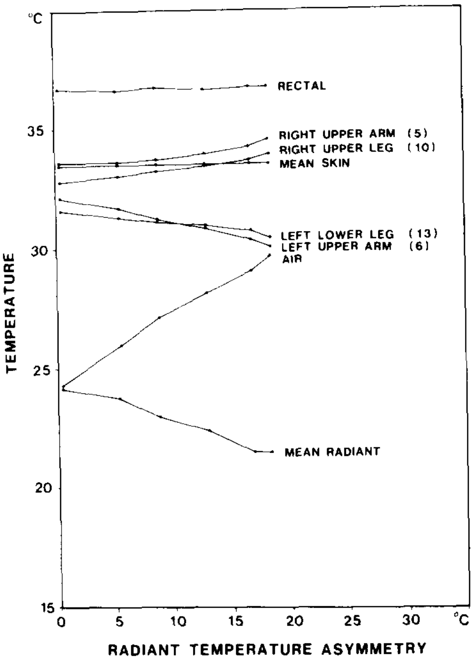

Fig. 9. *Cool wall:* rectal and skin temperature as a function of the radiant temperature asymmetry. Numbers refer to Fig. 2.

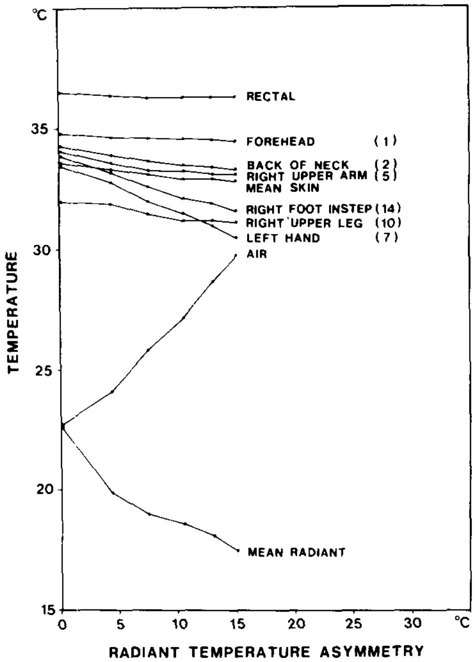

Fig. 11. *Cool ceiling:* rectal and skin temperatures as a function of the radiant temperature asymmetry. Numbers refer to Fig. 2.

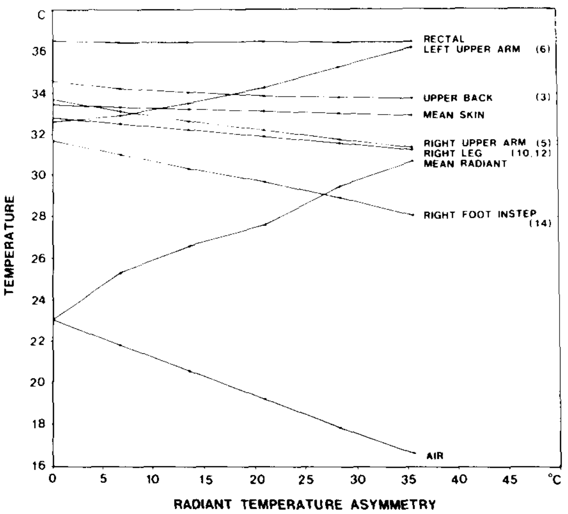

Fig. 10. *Warm wall:* rectal and skin temperatures as a function of the radiant temperature asymmetry. Numbers refer to Fig. 2.

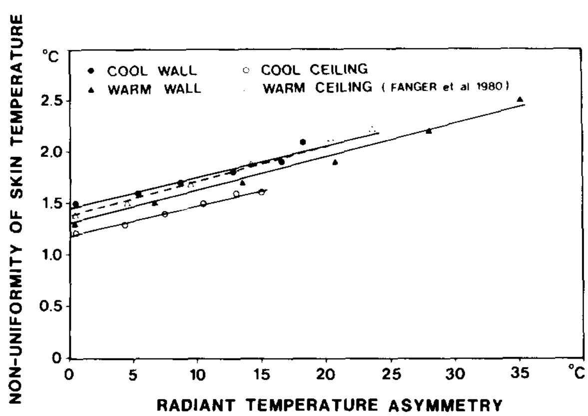

Fig. 12. The non-uniformity of the skin temperature as a function of the radiant temperature asymmetry.

Physiological measurements

In Figs. 9 - 11, mean values of the rectal and mean skin temperatures are shown as a function of the radiant asymmetry. These remained rather constant, independent of the increasing differences between the local skin temperatures at the different parts of the body when the radiation asymmetry increased. As suggested by Olesen and Fanger [7], 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 is shown in Fig. 12 as a function of the radiant asymmetry. It is remarkable to note that the lines are approximately parallel, i.e., that the non-uniformity of the skin temperature increased equally when exposed to radiant asymmetry, whether caused by a cool or warm wall, or by a cool or warm ceiling.

Figures 9 - 11 show also those local skin temperatures which changed most during exposure to radiant asymmetry. At the cool wall the left arm and leg, which were closest to the wall, had a decreasing skin temperature when the wall temperature decreased. At the warm wall the skin temperature of the closest (left) arm increased while the skin temperature of the right foot decreased. During the cool ceiling experiments the skin temperature at most locations decreased when the asymmetry increased. Even the mean skin temperature decreased slightly.

Measurements with the thermal manikin

The thermal manikin was used to determine the operative temperature in Tables 3 - 5 and in Fig. 4. It was also used to measure the changes in heat loss from different parts of the human body when exposed to radiant asymmetry. The results are shown in Figs. 13 - 15.

For the cool wall (Fig. 13) the heat loss from the left part of the manikin increased when exposed to growing asymmetry, while the heat loss from the right part decreased. Figure 14 for the warm wall shows a similar figure but with changes in the opposite direction. For the cool ceiling (Fig. 15) the heat loss increased from the upper part and decreased from the lower part of the manikin when exposed to growing asymmetry.

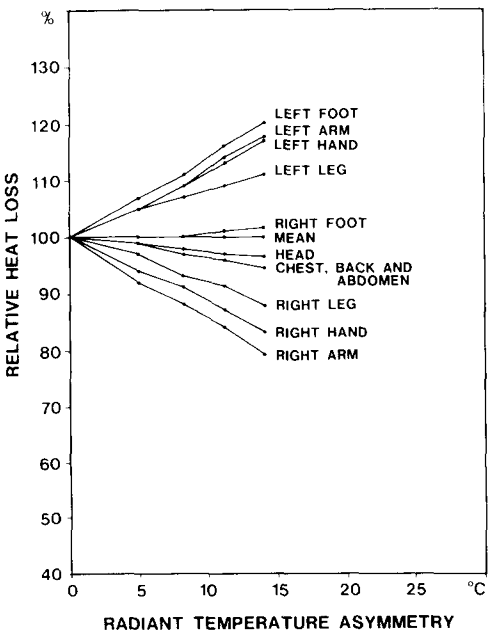

Fig. 13. *Cool wall:* the percentage change of the heat loss from the different sections of the thermal manikin when exposed to radiant asymmetry.

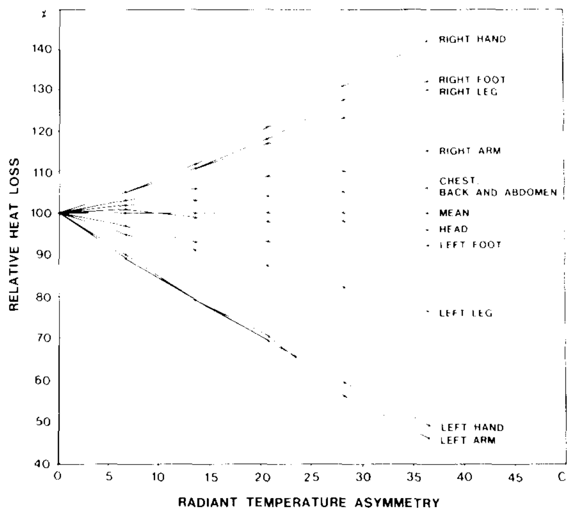

Fig. 14. *Warm wall:* the percentage change of the heat loss from the different sections of the thermal manikin when exposed to radiant asymmetry.

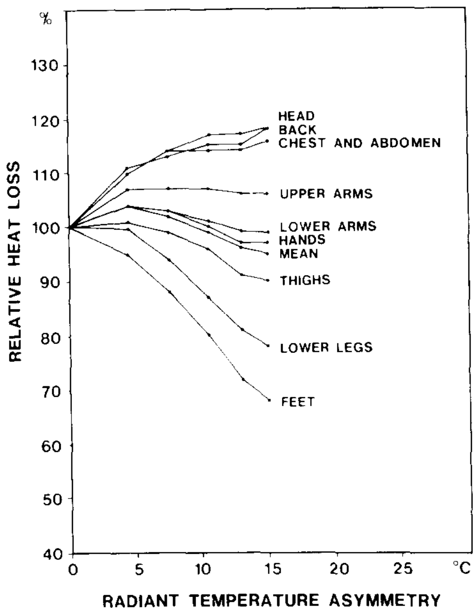

Fig. 15. *Cool ceiling:* the percentage change of the heat loss from the different sections of the thermal manikin when exposed to radiant asymmetry.

DISCUSSION

The most important results of the present study appear in Fig. 8 in the curves representing the percentages of people feeling uncomfortable when exposed to asymmetric radiation. It is remarkable to note the differrences in the discomfort caused by different types of asymmetry.

The subjects found the radiant asymmetry caused by a warm ceiling and a cool wall most uncomfortable, and it is these two cases for which limits have been set in existing standards and recommendations by ISO [11], ASHRAE [12] and NKB [13].

Accepting that 5% of subjects may feel uncomfortable, a radiant temperature asymmetry of 10 °C is acceptable for the cool wall (Fig. 8) and this is exactly what is recommended in the standards [11 - 13]. The 10 °C was also found as the 5% limit in a similar study for nude subjects by Olesen et al. [3].

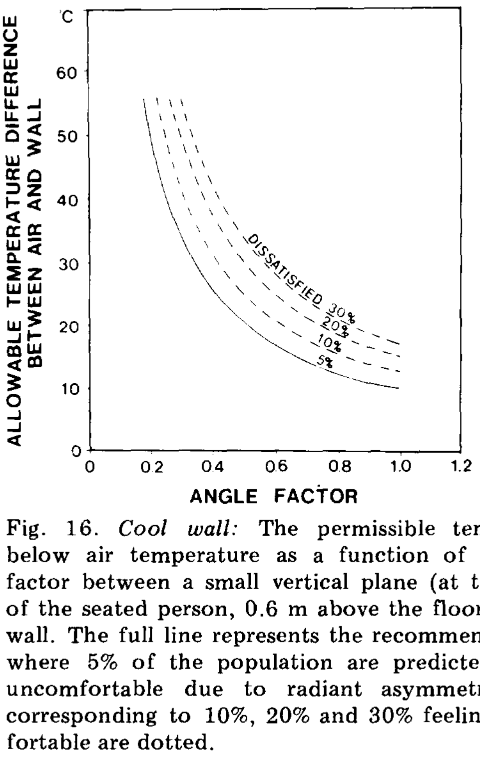

Fig. 16. *Cool wall:* The permissible temperature below air temperature as a function of the angle factor between a small vertical plane (at the centre of the seated person, 0.6 m above the floor) and the wall. The full line represents the recommended limit where 5% of the population are predicted to feel uncomfortable due to radiant asymmetry. Lines corresponding to 10%, 20% and 30% feeling uncomfortable are dotted.

For practical applications it may be easier to use Fig. 16 to predict the discomfort. From the temperatures of the cool wall, window or other vertical surface, and the corresponding angle factor [14], Fig. 16 makes it possible to predict the percentage of dissatisfied people caused by asymmetry and to check whether the standards are met.

The subjects were less bothered by the radiant asymmetry caused by the warm wall. They accepted more than twice as much asymmetry from the warm wall than from the cool wall. This is surprising. Owing to the symmetry of the human body, the same response could have been expected whether the lateral asymmetry was caused by a warm or a cool wall. The non-uniformity of the skin temperature for the two cases (Fig. 12) also suggests nearly the same change for the two cases. How could the substantial difference in discomfort then be explained?

From Table 6 it is obvious that discomfort from the cool wall was caused exclusively by a local feeling of cold on the left side of the body, while discomfort from the warm wall was caused both by a warm feeling at the left side and a cool feeling at the right side of the body (Table 7). This indicates that local cooling of the body is more frequently causing discomfort than local heating. From Figs. 9 and 10 it is obvious that the skin temperature of the left arm, being closest to the wall, changes most when exposed to radiant asymmetry. At this location the heat loss changes rapidly as shown by the manikin experiments (Figs. 13 and 14). It seems likely that a decrement of the local skin temperature is felt to be more uncomfortable than an increment. This may be the reason for the higher discomfort during exposure to a cool wall than to a warm wall.

The asymmetry under the cool ceiling (Fig. 8) was less uncomfortable than under the warm ceiling, studied by Fanger et al. [1]. A 3 - 4 times higher asymmetry was found acceptable under a cool ceiling. Most of the skin temperatures dropped during exposure to the cool ceiling, but only slightly, whereas at the feet the temperatures fell steeply during exposure to the warm ceiling. Cool feet were the cause of many complaints. The body is not symmetrical in relation to a horizontal plane, and therefore it is easy to understand a difference in the impact of a cool or warm ceiling. The present results support the traditional recommendation of "keeping the head cool and the feet warm".

Another interesting observation is that the operative temperature preferred by the subjects was constant while exposed to the warm wall and the warm ceiling [1], while slightly increasing during the cool wall and ceiling experiments (Fig. 4). A slight increase in the preferred operative temperature has been found after the first hour in several earlier studies [5, 14], probably caused by a slightly decreasing metabolic rate.

No significant differences were found in the responses of females and males to asymmetric radiation. This agrees with other studies on local discomfort caused by a vertical air temperature difference [15], a warm or cool floor [16], or a too high velocity [17].

It should be noted that the present study was performed with sedentary subjects in thermal neutrality. For persons at higher activity no data are available, although in general, sedentary persons seem to be most sensitive [14]. For people feeling too warm or cool for the body in general other asymmetry limits may apply.

The results were obtained for radiant asymmetry caused by low temperature sources, i.e., longwave radiation. For high temperature sources and shortwave radiation (e.g., from the sun or from infrared heaters) the absorption at the skin may be different and other limits of asymmetry may apply.

CONCLUSIONS

For cool walls, warm walls, and cool ceilings, curves have been established showing the percentage of dissatisfied subjects as a function of the radiant temperature asymmetry (Fig. 8).

Radiant asymmetry at a warm wall caused less discomfort than at a cool wall. A cool ceiling caused less discomfort than a warm ceiling.

Accepting that 5% of subjects may feel uncomfortable, a radiant temperature asymmetry of 10 °C was found permissible at a cool wall, 23 °C at a warm wall and 14 °C under a cool ceiling. A previous study [1] found 4 °C permissible under a warm ceiling.

Radiant asymmetry had no significant impact on the operative temperature preferred by the subjects.

No significant differences were observed between the responses of men and women exposed to radiant asymmetry.

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