Reprinted from Proceedings of the CIB Commission W45 (Human requirements) Symposium: THERMAL COMFORT AND MODERATE HEAT STRESS, Building Research Station, London September, 1972. Published by HMSO 1973.

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COMFORT LIMITS FOR MAN EXPOSED TO ASYMMETRIC THERMAL RADIATION

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Sixteen college-age subjects were tested individually in a climate chamber. A pair of opposite walls could be held at different temperatures, while keeping the mean-radiant temperature constant. Each subject, virtually naked, selected that uniform environment which rendered him thermally neutral. The asymmetry was then increased in steps at half-hour intervals until the temperature difference between opposite walls was 40°C. Judgements of perception of asymmetry and discomfort from asymmetry were obtained for three orientations of the subjects. A formula is derived for the upper limit of comfortable local radiant exposure, for clothed persons in thermal neutrality. *(Ed. abstract)*

Introduction

The purpose of this study has been to estimate experimentally the limit of the asymmetric thermal radiant field to which persons in thermal neutrality can be exposed without considering the surroundings uncomfortable. Thermal neutrality for a person is defined as the condition in which the subject prefers neither warmer nor cooler surroundings. Thermal neutrality is a necessary condition for a person to attain thermal comfort. However, the condition is not sufficient because upper limits exist for the dissimilarity of clothing, air velocity, air temperature and radiant temperature above which the person will consider the surroundings uncomfortable. Moreover, according to Olesen *et al,*[16] the combination of parameters is apparently unimportant when the individual variables are uniform and the combination is in agreement with Fanger's[3,5] comfort equation.

Several investigators have studied the influence of asymmetric radiant fields on thermal comfort. The fields were created, for example, by warm or cold panels in a wall or in the ceiling: Bøje *et al,*[1] Chrenko[2], Gagge[6,7,8], Hall and Klemm[9], Kollmar[11,12,13], McNall and Biddison[14], Ronge and Löfstedt[18], Schlegel and McNall[19], Wenzel and Müller[21]. From these studies, which have been discussed by Fanger[5], it is difficult, however, to estimate comfort limits for asymmetric radiation of persons in thermally neutral environments. This study has therefore been conducted to provide estimates of those limits.

Subjects

Sixteen healthy college-age subjects (8 females and 8 males) were tested individually. They were all volunteers and were paid for their participation. Each subject participated in four 3-hour tests but in each test only one subject participated. Anthropometric data for the subjects are listed in Table 1.

Clothing

The male subjects wore only cotton briefs and shorts, while the females wore bikinis. The clo-values of both types of clothing were approximately 0.1 clo. Light clothing was chosen in order to maximize the radiation sensitivity.

Experimental Facilities

The experiments were carried out in the environmental chamber at the Laboratory of Heating and Air Conditioning, Technical University of Denmark. In the chamber (2.8 m x 4.5 m x 2.8 m) all relevant combinations of air temperature, air humidity, air velocity and mean radiant temperature were accurately controlled. The ceiling of the chamber, floor and side walls were covered with high gloss aluminium plates, which made it possible to regulate the radiant temperature in the two half-rooms of the chamber independently of each other by means of the water-filled end walls in the chamber. The chamber and its apparatus have been described in detail by Olesen[15]. During the experiments, the mean skin temperature and rectal temperature of the subjects were measured using a 'harness' consisting of 28 skin temperature thermistors and one rectal thermistor. (Yellow Springs, Series 400).

Conditions

Maintenance of the surroundings to provide thermal neutrality for each person was necessary. Therefore, the temperature level of the surroundings during each test was regulated according to the subject's wishes. In the first part of each test the temperature of the end walls was kept equal to the air temperature to ensure that the subject was in thermal comfort before exposure to the asymmetric radiant fields. By decreasing the water temperature in one of the end walls and correspondingly increasing the temperature of the opposite wall in steps of 5°C every 30 minutes, the mean radiant temperature in the middle of the chamber was kept equal to the air temperature while the asymmetry of the radiant field was gradually increased. The subject was seated in the middle of the chamber on a chair with a seat and back of plastic strips which influenced only slightly the subject's heat loss to the environment. The subjects were exposed respectively with one side, front and back toward the cold wall. During each test, the water vapour pressure was maintained at 14 mm Hg and the air velocity at less than 0.1 m/s.

TABLE 1. Anthropometric data for the subjects

	Subject No.	Age Years	Body Height cm	Body Weight kg	DuBois Area m^2
	1	28	181	72.3	1.92
	2	24	173	62.3	1.74
M	3	26	176	72.9	1.89
A	4	23	189	72.9	1.98
L	5	23	188	77.9	2.03
E	6	22	173	67.0	1.80
S	7	23	175	65.3	1.84
	8	21	182	66.1	1.86
	Mean	23.8 ±2.1*	179.6 ± 6.0	69.6 ±4.9	1.88 ±0.09
	1	25	172	59.8	1.71
F	2	24	168	55.0	1.62
E	3	25	160	50.3	1.51
M	4	23	165	55.8	1.61
A	5	22	153	45.9	1.40
L	6	28	168	51.1	1.57
E	7	20	168	58.6	1.67
S	8	20	171	57.0	1.67
	Mean	23.4 ±2.6	165.6 ± 5.9	54.2 ±4.4	1.60 ±0.09
Mean for all 16 Subjects		23.6 ±2.3	172.6 ± 9.2	61.9 ±9.0	1.74 ±0.17

*Standard Deviation

Procedure

The subject reported at least 30 minutes prior to the commencement of the experiment. It was ascertained that he had slept sufficiently, had no fever, had consumed normal meals but no alcohol during the previous 24 hours. The subject donned the 'thermistor harness' and the thermistors were taped to the skin with surgical tape. The subject entered the environmental chamber where, after weighing at time $\tau = 0$ minutes he was seated in the chair. The first time a subject was tested, the ambient temperature was 28°C at the start of the test since this, according to Fanger's[3,5] comfort equation, is the temperature most likely to provide thermal comfort. In subsequent tests the temperature was set initially at that preferred by the subject during his previous test. Therefore it was possible to decrease the time necessary to obtain optimal thermal comfort of the subject. Every 10 minutes (τ = 3, 13, 23 . . . minutes) the subject responded to the questions shown in Fig.1. Before the start of the test, the end walls were shown to him and he was told that the temperature of these walls would be changed (but not how and when). The purpose of the first question was to maintain the surroundings at thermal neutrality for the subject, as the air temperature and the mean radiant temperature were continually changed according to the wishes of the subject. The subsequent questions provided a direct estimation of the limits of sensation and comfort for each subject.

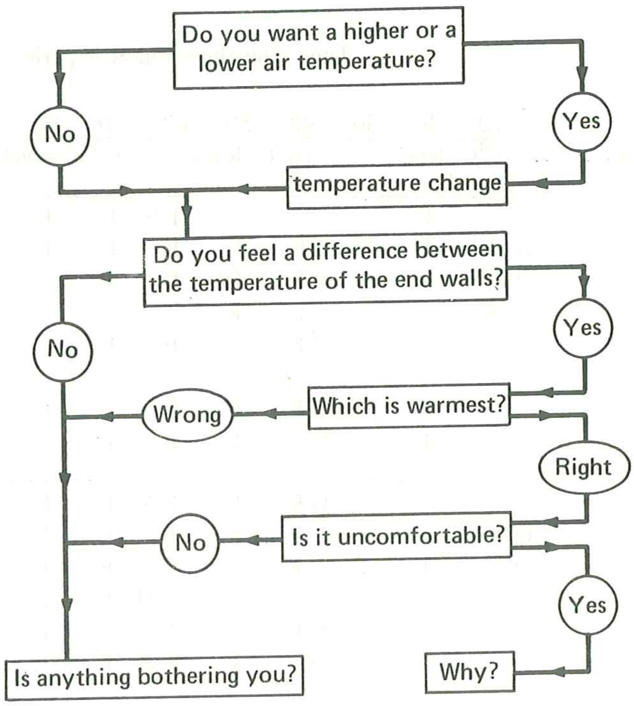

Figure 1. *Questions for evaluating subjects' responses to assymetric radiation.*

The first time a subject was tested the end wall temperatures were maintained equal to the air temperature until time τ = 53 minutes, and in subsequent tests until τ = 23 minutes for reasons previously explained. After this initial period the temperatures were changed in opposing increments of 5°C every 30 minutes (i.e. the end wall temperatures were maintained at 0, ±5, ±10, ±15 and ±20°C differentials with respect to the air temperature). The duration of the asymmetric period was 2 hours, and the duration of the entire test was 3 hours for the initial tests and 2½ hours for the subsequent tests. Every 5 minutes all temperatures were registered by means of the datalog system in the chamber (τ = 2, 7, 12, . . . minutes). The subject was weighed, seated on a scale in the chamber at the start of the test, at the beginning of the asymmetric period and at the end of the test.

Results

The results of the physiological measurements will not be included in this paper.

Tables 2 and 3 show the subjects' judgments of their exposure to the asymmetric radiation under each experiment. F indicates that the subject could sense the asymmetry and U indicates that he felt the asymmetry as uncomfortable. As the judgments of the individuals have not been highly reproducible, it has been necessary to choose a set of criteria to establish the limits for sensation and discomfort.

Sensation Criteria for One Person

The lowest level of asymmetry at which a subject indicated sensation or discomfort at least twice during that time interval and during following intervals of greater levels of asymmetry, if any.

Discomfort Criteria for One Person

The lowest level of asymmetry at which a subject indicated discomfort at least twice during that time interval and during following intervals of greater levels of asymmetry, if any.

TABLE 2. Thermal judgments of different asymmetric radiation exposures for females

Female No.	Type of Experiment	Time after the symmetric period (min.) 10	20	30	40	50	60	70	80	90	100	110	120
		5^{o}C–level			10^{o}C–level			15^{o}C–level			20^{o}C–level		
1			F				F X	U	F	U	U	U	U
2	cold	O F	F	F	F	F	F	F	F	F X	U	U	U
3	left	O F	F	F	F	F	F	F	F	F	F	F	F
4	and	F			F	F				F O	F	F	F
5	warm				O F		F	F		F	F	U	F
6	right										O	F	F
7					O F	F	F	F	U	F	F	F	F
8			F		O	F	F	F		F X	U	U	U
1					O F	U	F X	U	U	U	F	U	U
2	warm	O F	F	F	F	F	F	F	F		X U	U	U
3	left	O	F	F	F	F	F	F	F	F	F	U	F
4	and							O F	F	F	F	U	F
5	cold			F	O F	F	F	F	F	F X	F	U	U
6	right				O	F	F X	U	F	U	U	U	U
7										F O	U	F	
8		O F	F	F	F	F	F	F	F	F X	U	F	U
1		F						O F	F	F	F	F	F
2	cold	O F	F			F	F	F	F	F	F	F	F
3	front				O F	F	F	F	F	F	F	F	F
4	and									F O	F	F	F
5	warm	O F	F	F	F	F	U	F	F	F	F	F	F
6	back			F	O F	F	F	F		U X	U	F	U
7						F	F				F		
8		F	F	F			F O	F	F	F	F	U	F
1		F			F	F	F	F	F				
2	warm	F			O F	F		X U	U	U	U	U	U
3	front	O F	F	F	F	F	F X	U	U	F	F	U	U
4	and					F			F		O F	F	F
5	cold				O U	F	F	U	U	F	F	F	F
6	back	F				F						F	
7								O	F	F	F	U	F
8		O F	F		F	F	U	F	F		X U	U	

F: The subject could sense the asymmetric radiation
U: The subject found the asymmetric radiation uncomfortable
O: Limit for sensation
X: Limit for comfort

TABLE 3. Thermal judgments of different asymmetric radiation exposures for males

Male No.	Type of Experiment	10	20	30	40	50	60	70	80	90	100	110	120
		5^oC–level			10^oC–level			15^oC–level			20^oC–level		
1		O F		F	F	F	F	F	F	U X	U	U	U
1					O F	F	F	F	F	F X	F	U	U
2			U		U								
2											O F	F	F
3	cold			U		U	F	F	F				F
3	left		U										F
4	and	O F		F	F		F	F	F	F X	U	U	U
5	warm			F	O F	F		X U	U	U	U		U
6	right	F			U	F				F X	U	U	U
6					U	U			U		O U	M	
6													F
7		O	F	F	F	F	F	F	F	U X	U	U	
8				F	O F	F	F	F	F	F	F	U	F
1		O	F	F	F	F	F		F	F	F	F	F
2	cold				F	F							
4	front	F			O F	U	F	F	U	F	F	F	F
6	and							O	F	F	F	F	F
7	warm									F X	U	U	F
8	back					F		O	F	F	F	F	F
1								O	F	F	F	F	F
2	warm				F						O	F	F
3	front			F						U			
4	and	O	F	F	F	F	F	F	F	F X	U	U	
5	cold	O U	U	F	F	F	F	F	F	F	F	F	U
6	back							U					
7					O F	F	F	F	F	F X	U	U	U

Time after the symmetric period (min.)

F: The subject could sense the asymmetric radiation
U: The subject found the asymmetric radiation uncomfortable
O: Limit for sensation
X: Limit for comfort

Tables 4 and 5 show respectively the number of subjects who were able to sense the asymmetric radiation and the number who found the radiation uncomfortable at any temperature level under the different types of exposure listed, together with the corresponding relative cumulative frequencies. As shown, each subject has been equally weighted by individual and not by number of tests. Assuming normal distribution of the limits of asymmetry, the relative cumulative frequencies may be described as straight lines on probability graph paper from which the mean value and the standard deviation for each distribution can be estimated. As the number of subjects was limited, the relative cumulative frequencies can only be described approximately as straight lines. Therefore the lines have been estimated by linear regression, which was possible as the values of the extremes of 0 and 100% were not included.

TABLE 4. Number of subjects able to sense different levels of asymmetric radiation (N) and corresponding relative cumulative frequencies (Rf) for different types of experiments

Type of Experiment	Sex	Number of Experiments	5°C–level N	5°C–level Rf %	10°C–level N	10°C–level Rf %	15°C–level N	15°C–level Rf %	20°C–level N	20°C–level Rf %
cold left-warm right	female	8	2	25.0	5	62.5	6	75.0	8	100
warm left-cold right	female	8	3	37.5	6	75.0	7	87.5	8	100
cold left-warm right	male	16	6	37.5	11	68.8	11	68.8	13.3	83.3
warm front-cold back	female	8	2	25.0	4	50.0	5	62.5	6	75.0
warm front-cold back	male	7	2	28.6	3	42.9	4	57.1	5	71.4
cold front-warm back	female	8	2	25.0	4	50.0	6	75.0	7	87.5
cold front-warm back	male	6	1	16.7	2	33.3	4	66.7	5	83.3
All	female & male	61	18	29.5	35	57.3	43	70.4	52.3	85.8

TABLE 5. Number of subjects finding different levels of asymmetric radiation uncomfortable (N) and corresponding relative cumulative frequencies (Rf) for different types of experiments

Type of Experiment	Sex	Number of Experiments	15°C–level N	15°C–level Rf %	20°C–level N	20°C–level Rf %
cold left-warm right	female	8	1	12.5	3	37.5
warm left-cold right	female	8	2	25.0	5	62.5
cold left-warm right	male	16	2	12.5	8.7	54.2
warm front-cold back	female	8	2	25.0	3	37.5
warm front-cold back	male	7	0	0	2	26.5
cold front-warm back	female	8	0	0	1	12.5
cold front-warm back	male	6	0	0	1	16.7

Tables 6 and 7 list respectively the results from the comparisons between different groupings of sensations and comfort judgments. The comparison between standard deviations was made by Bartlett's test and between mean values by the t-test. Since the males were exposed to cold left and warm right side, and not warm left and cold right, the first comparison was made between females exposed to cold left and warm left side. No significant differences between the two types of exposures were detected and, therefore, a comparison between the two sexes was possible. The judgments of females and males did not deviate significantly; therefore, the remainder of the tests were analyzed for females and males pooled in steps as shown in Tables 6 and 7. Only two of the subjects found the 20°C level uncomfortable and none found the 15°C level uncomfortable when exposed with front toward the cold half-room. Therefore it was impossible to identify the distribution of comfort judgments directly in this case. By assuming the same standard deviation for the distribution as for the other exposures, the distribution was identified indirectly. Table 6 shows that no significant differences between the different types of exposure were detected for judgments of sensation. This indicates that the subjects could sense the asymmetric radiation at a certain level independently of the direction they were facing. For the distribution of all judgments of sensation the mean value was 9.4°C and the standard deviation 9.5°C. For the comfort judgments in Table 7 significant differences were detected only between the exposures with front toward the cold half-room as compared with all the other exposures. This indicates that the subjects accepted a higher degree of asymmetric radiation when they were exposed with fronts toward the cold half-room.

All the temperature levels mentioned thus far are, as stated earlier, differences between the air temperature and the end-wall temperature and not the difference between air and mean radiant temperature in each of the two half-rooms. Several radiometer measurements have shown that the radiant temperature in each half-room was highly uniform and that a difference between air and end-wall temperature of 10.00°C corresponded to a difference of 3.92°C between air and mean radiant temperature of that half-room. Expressed as the change of mean radiant temperature in one half-room, the mean value of the limit μ, and the standard deviation, σ, for all judgments of sensation will both be 3.7°C. For comfort judgments, from experiments with side or back toward the cold wall, (μ, σ) will be (8.0°C, 2.0°C) and from tests with front toward the cold wall (μ, σ) will be equal to (10.1°C, 2.0°C). It is possible to calculate the number of persons in a random group, who will find a certain asymmetric exposure uncomfortable, from these distributions. A limit at which 5% of a group will be uncomfortable is recommended, as this percentage commonly occurs in the literature.

TABLE 6. Comparison between different distributions of sensation limits of asymmetric radiation

Groups (S: Side, L: Left, R: Right, F: Front, B: Back, C: Cold, W: Warm)	Number of Subjects	Mean of End Wall Temp. Change $\hat{\mu}$ °C	Standard Deviation $\hat{\sigma}$ °C	Difference Between Standard Deviations (Bartlett's test): Degrees of Freedom	χ^2-value	Significance (5% level)	Difference Between Mean Values (t-test): Degrees of Freedom	t-value	Significance (5% level)
CL-WR Female	8	9.2	7.4	1	0.31	no	14	0.62	no
WL-CR Female	8	6.6	6.9						
Female	8	9.2	8.1	1	0.75	no	14	0.14	no
Male	8	9.9	11.4						
S-S Female & Male	16	7.2	9.1	1	1.25	no	29	1.24	no
WF-CB Female & Male	15	12.0	12.3						
S-S+ WF-CB Female & Male	16	8.9	10.2	1	0.54	no	28	0.68	no
CF-WB Female & Male	14	11.2	8.0						

TABLE 7. Comparison between different distributions of discomfort limits in asymmetric radiant fields

Groups S: Side B: Back L: Left C: Cold R: Right W: Warm F: Front	Number of Subjects	Mean of End Wall Temp. Change $\hat{\mu}$ °C	Standard Deviation $\hat{\sigma}$ °C	Difference Between Standard Deviations (Bartlett's test): Degrees of Freedom	χ^2-value	Significance (5% level)	Difference Between Mean Values (t-test): Degrees of Freedom	t-value	Significance (5% level)
CL-WR Female	8	20.2	4.5	1	0.09	no	14	0.75	no
WL-CR Female	8	18.4	5.1						
Female	8	22.3	7.3	1	2.06	no	14	0.44	no
Male	8	21.0	4.1						
S-S Female & Male	16	19.7	4.7	1	2.99	no	29	1.58	no
WF-CB Female & Male	15	23.2	7.4						
S-S+ WF-CB Female & Male	16	20.5	5.2	–	–	–	28	2.74	yes
CF-WB Female & Male	14	25.7	5.2*						

*Estimated equal to the standard deviation for the other exposures.

Formula for the upper limit of comfortable local radiant exposure for clothed sedentary persons in thermally neutral environments in still air

Consider a unit skin area directed against a deviating radiant field (i.e. a cold source of radiation). It has been found that the limit of discomfort for the area will be reached, for 5% of a group of persons, when the mean radiant temperature, t_{mrt}, is lowered $5^{o}C$* in relation to the unit area. From the present skin temperature measurements, it was found that a lowering of $5^{o}C$ in t_{mrt} will result in a lowering of the skin temperature t_s of $1^{o}C$. This corresponds to a change of the heat flux H approximately equal to the sum of the changes of the convection C and the radiation R from the skin. When the air temperature t_a and t_{mrt} are $28^{o}C$ and t_s is $33.6^{o}C$ (i.e. corresponding to the mean values measured under the present study and to the t_s in Olesen & Fanger[17]), ΔH can be calculated from Fanger's[3] equations for C and R:

$$\begin{aligned}\Delta H = \Delta C_o + \Delta R_o &= 2.05\,[(32.6-28)^{1.25} - (33.6-28)^{1.25}] \\ &\quad + 3.4 \times 10^{-8}(305.6^4 - 296.0^4 - 306.6^4 + 301.0^4) \\ &= 10.5 \text{ kcal/m}^2\text{hr} \qquad (1)\end{aligned}$$

If the skin area is covered by clothing with a clo-value of I_{cl}, the maximum decrease of the outer surface temperature of the clothing t_{cl} can be calculated when ΔH and Δt_s are known from the following equation:

$$\Delta t_{cl} = -\Delta H \times 0.18 I_{cl} + \Delta t_s = (-1.9 I_{cl} - 1)^{o}C \qquad (2)$$

This decrease of t_{cl} is caused by a maximum decrease of t_{mrt} in the half-room facing toward the unit area. The maximum Δt_{mrt} can be calculated from the following equation:

$$\Delta H = \Delta C_1 + \Delta R_1 \qquad (3)$$

where

$$\Delta C_1 = f_{cl} \times 2.05\ [(t_{cl} + \Delta t_{cl} - t_a)^{1.25} - (t_{cl} - t_a)^{1.25}] \qquad (3a)$$

and

$$\Delta R_1 = f_{cl} \times 3.4\ 10^{-8}[(T_{cl} + \Delta t_{cl})^4 - (T_{mrt} + \Delta t_{mrt})^4 - T_{cl}^4 + T_{mrt}^4] \qquad (3b)$$

f_{cl} is the ratio of the surface area of the clothed body to the surface area of the nude body. If the water vapour pressure is kept at 12 mm Hg, which corresponds to a relative humidity of 50% when $t_a = 25.6^{o}C$, the subject's heat loss by evaporation, E, and dry respiration, L, will be approximately 11 kcal/m²hr (Fanger[5]). Since a subject's preferred t_s does not depend on his clothing (Olesen[15]), t_{cl} can be calculated from the following equation:

$$t_{cl} = t_s - (H - E - L) \times 0.18 \times I_{cl} = (33.6 - 7.0 I_{cl})^{o}C \qquad (4)$$

Assuming that t_a and t_{mrt} are equal, the following approximate equation (3) can be used to estimate the neutral temperature level:

$$t_a = t_{mrt} = 28.5 - 5 I_{cl}\ ^{o}C \qquad (5)$$

Substituting the expressions for ΔH, Δt_{cl}, t_{cl}, t_a and t_{mrt} given by equations [1], [2], [4] and [5] in the heat balance equation [3]:

$$\begin{aligned}10.5/f_{cl} &= 2.05\,[(4.1 - 3.9 I_{cl})^{1.25} - (5.1 - 2 I_{cl})^{1.25}] \\ &\quad + 3.4 \times 10^{-8}[(305.6 - 8.9 I_{cl})^4 - (301.5 - 5 I_{cl} + \Delta t_{mrt})^4 \\ &\quad - (306.6 - 7 I_{cl})^4 + (301.5 - 5 I_{cl})^4] \qquad (6)\end{aligned}$$

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*The $5^{o}C$ stands for cold exposure of back and sides.

This expression can be simplified to the following equation with good approximation:

$$|\Delta t_{mrt}| = (5 - 2.4\,(f_{c1} - 1) + 3.6 I_{c1})^{o}C \qquad (6a)$$

The angle factor between a person and a local radiant source is normally less than 0.5; therefore it will only occasionally be possible to use equation [6a] directly. Since t_{mrt} for a half-room can be calculated as the mean value of the surrounding temperatures weighted according to the magnitude of the respective angle factors (i.e. for relatively small temperature difference between the surfaces of the enclosure) equation [6b] can be used to estimate the maximum permissible deviation of a given surface temperature, t_w, from the other surface temperatures:

$$|\Delta t_w| \leqslant (2.5 - 1.2(f_{c1} - 1) + 1.8 I_{c1})/F_{p\text{-}w} \quad {}^{o}C \qquad (6b)$$

where $F_{p\text{-}w}$ is the angle factor between the person and the actual source of radiation. Angle factors can be estimated from diagrams of Fanger *et al.*[4,5]

Discussion

The results show that the subjects could sense relatively small degrees of asymmetric radiation and that the asymmetry had to be increased significantly above the sensation level before the exposure was found to be uncomfortable. The subjects accepted the highest degree of asymmetry with front toward the cold half-room, and the subjects most often expressed their discomfort because of local cooling. This greater tolerance can perhaps be due to the subjects' faces having adapted previously to greater variations in heat flux combined with a greater initial radiation between the seated subjects' frontal areas.

In the statistical analysis, no significant difference was found between the reactions of females and males to the asymmetry. If the pooled comparison or the limited number of experiments were the reasons for the lack of significance then the distributions mentioned can be considered as being the mean distributions for females and males.

As mentioned earlier, the cold radiant asymmetry determined by equation (6b) corresponds to the limit at which 5% of the population will find discomfort, when seated with the back or side to the radiant source. For frontal exposures toward the source the formula states the limit for 1% of the population. Since the subjects were exposed in uniform half-rooms it is reasonable to assume that formula [6b] is also valid for cold ceilings. As mentioned, the discomfort was most often due to local cooling. The limit for warm radiation asymmetry seems therefore to be higher than the one estimated by formula [6b]. Chrenko[2] has suggested an upper limit of 2^{o}C in the half-room over a unit area of head. However, his subjects were probably not thermally neutral. A stipulation of the upper limit can be found from McNall and Biddison's[14] recent series of experiments. Their subjects were clothed in the KSU-uniform ($I_{c1} = 0.6$ and $f_{c1} = 1.2$) and seated with either an angle factor 0.12 to a warm ceiling or with an angle factor 0.20 to a warm wall. A ceiling temperature 38^{o}C higher than room temperature was not uncomfortable in contrast to a wall temperature elevation of 25^{o}C. This corresponds respectively to temperature elevations of 9.1^{o}C and 10^{o}C for a half-room. Assuming the limit to be 9.6^{o}C, a new first constant in equation [6b] can be calculated as 4.0^{o}C by solving the equation [6b] for $t_w = 9.6^{o}$C. A double asymmetry equation is therefore:

$$-2.4 - 1.8 I_{c1} \leqslant \Delta t_w\, F_{p\text{-}w} \leqslant 3.9 + 1.8 I_{c1} \qquad (7)$$

where the value 1.1 has been used for f_{c1}. This value represents an average value for most normal clothing. Since higher activity levels are often correlated to rotational movement of the body in relation to the radiant field, both higher activity levels and velocities will result in higher asymmetry limits.

The influence of the size of the exposed body area has been studied by Hardy and Oppel[10] and Turner[20]. Both studies showed that the maximum intensity of the radiation was independent of the size of the body area when the area was greater than 100 cm^2. Since body areas exposed to local radiation sources are seldom smaller than 100 cm^2, formula [7] can be used directly without corrections for area size.

Bøje *et al*[1] have indicated that asymmetric radiation exposure can produce unfavourable effects on the state of health over prolonged exposures even at levels less than those required to produce discomfort. Therefore, it is possible that further health oriented research will result in recommendations for lower limits than those suggested herein.

Conclusions

1. For subjects in thermal neutrality no significant difference was found between female and male reaction to asymmetric radiation.
2. 50% of the subjects were able to sense the asymmetric radiation when the difference in radiant temperature between two half-rooms was 7.4°C independent of the direction in which the naked subjects were facing.
3. In thermal neutrality 5% of the groups found a 5°C decrease of the radiant temperature in one half-room uncomfortable when they sat with side or back toward the cold half-room, whereas a difference of 6.6°C caused discomfort when they were exposed to cold from the front.
4. The following formula for estimating the limits of acceptable temperature differences of a local radiant source for sedentary persons in thermally neutral environments with still air is recommended:

$$-2.4 - 1.8I_{cl} \leqslant \Delta t_w F_{p\text{-}w} \leqslant 3.9 + 1.8I_{cl}$$

where I_{cl} = clo-value of clothing

$F_{p\text{-}w}$ = angle factor between person and radiant source

Δt_w = temperature difference (°C) between radiant source and mean radiant temperature in relation to the person.

Acknowledgement

The authors wish to acknowledge their thanks to Mr. James E. Woods, Institute for Environmental Research, Kansas State University. The study has been supported by the Danish Government Fund for Scientific and Industrial Research.

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SUPPLEMENT

Equation (7) can be changed, so that a comparison can be made with the comfort limits for heated ceilings established by Chrenko[2] and Banhidi[22]. By introducing the angle factor between the most severely exposed body area and the radiant source, equation (7) will be as follows:

$$-4.8 - 3.6\, I_{cl} \leqslant \Delta t_w F_{a-w} \leqslant 7.7 + 3.6\, I_{cl} \tag{7a}$$

where I_{cl} = clo-value of clothing

F_{a-w} = angle factor between the most severely exposed body area and radiant source

Δt_w = temperature difference (^{o}C) between radiant source and mean radiant temperature in relation to the person.

The right side of equation (7a) is shown graphically in Figure 2 (I_{cl} = 1 clo). Equation (7a) corresponds to 5% uncomfortable, but similar curves for 1% and 10% uncomfortable are also shown in Figure 2. For comparison, the curves of Chrenko[2] and Banhidi[22] are graphed, showing comfort limits for heated ceilings. The results of Chrenko seem conservative compared to those of the present study, even though he accepts 20% as being uncomfortable. A reason for this difference might be that some of his subjects possibly have in general been too warm under the exposure to the asymmetric radiation. Banhidi[22] has not mentioned his percentage of dissatisfied so a direct comparison with his results is difficult. His limit is higher than that of the present study for angle factors higher than approximately 0.3 and lower for factors lower than 0.3.

It should be noted that equation (7a) should be used rather than equation (7) in cases where the distance to the radiant source is not great in relation to the distance between the body centre and the most severely exposed body area. In equation (7) the relationship between the two angle factors has been assumed to be constant. This assumption is incorrect when the body is close to the radiant source.

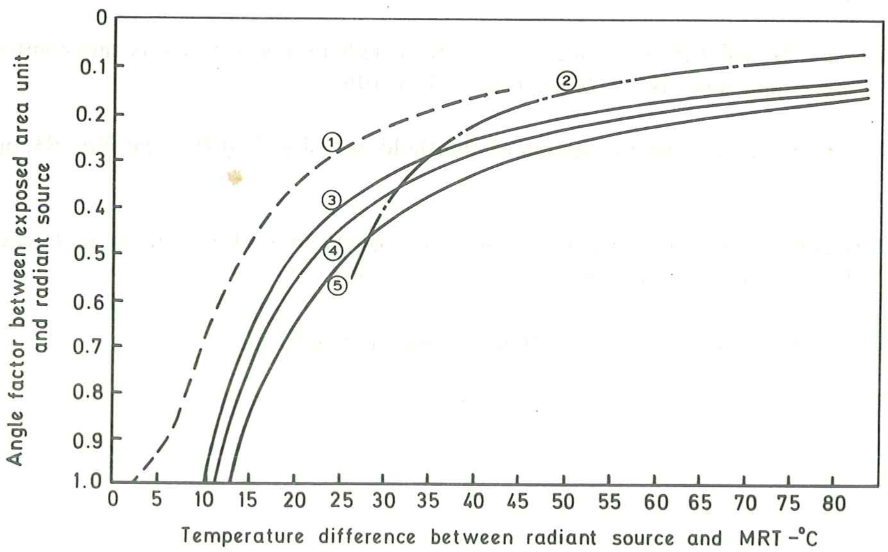

Figure 2. *Comfort limits for warm radiation asymmetry from the present study compared with results by Chrenko (2) and Banhidi (22). ① Chrenko A curve. ② Banhidi A curve. ③, ④ and ⑤ are comfort curves from the present study for different percentages of dissatisfied (1, 5 and 10%) of a group of persons with a clo-value of 1.*

DISCUSSION

Dr. M. Jokl: How do you define the axis of symmetry?

Mr. Olesen: In our experiments the axis is the vertical line through the centre of the body.

Dr. Jokl: If you were dealing with ceiling heating, it would be quite different?

Mr. Olesen: I am not sure of that. The radiation from the end walls was reflected on the other surfaces (polished aluminium plates) so the radiation came uniformly from all directions in each half-room.

Mr. P.W. Fitt: What surface did you have on the radiant panels? I am wondering about the emissivity.

Mr. Olesen: They were painted steel surfaces, and there was a sheet of polyethylene between the panel and the room (polyethylene is transparent to the infra-red). The other walls, the ceiling and the floor were covered with aluminium plates.

Mr. Fitt: So the radiant surface as seen by the subject is aluminium, or paint?

Mr. Olesen: It is paint, or the reflection of the painted surface, seen in the plates. The aluminium reflects 96 per cent of the radiation.

Mr. M.A. Humphreys: In McIntyre and Griffiths' warm ceiling experiment, and in your asymmetric wall experiment, it seems that the subjects complain mostly of cold. Is it possible to trade off asymmetry by raising the general temperature?

Mr. Olesen: By raising the temperature level and keeping the temperature difference between the end walls constant the degree of asymmetry will be constant. Nevertheless, fewer subjects will find the asymmetry uncomfortable. Some will start complaining of the warm radiation while more subjects will stop complaining of cold radiation. However, a few subjects will now complain of general warmth discomfort.

Mr. Humphreys: Referring to your questionnaire, when you ask your subject which wall is warmer, if he gives a wrong answer, do you ignore it? I am a little worried by the asymmetry of the questionnaire, which perhaps could over-estimate the degree of complaint.

Mr. Olesen: No, we check him again by asking him if anything is bothering him.

Dr. Ann Davies: This work applies to nude subjects at temperatures of about 28^{o}. The application would therefore appear to be relatively slight. Can you give a general justification for this type of work?

Mr. Olesen: I have tried to do so in the presentation of this paper. The limitations of our climate chamber did not permit us to test heavier clothing by this method. The end walls are heated or cooled by water, so we had to keep the end wall temperatures higher than approx. 5^{o}C. Furthermore, we expected a nude subject to be most sensitive to radiation asymmetry.

Dr. A. Davies: Would you then regard your experiment as a first approximation for clothed conditions?

Mr. Olesen: It is easy to apply these results to clothed subjects. The calculation is explained in the paper.

Mr. J.F. Nicol: In all cases, you slowly increased the asymmetry, and this could affect the results. If you had started with maximum asymmetry and then reduced it, you might have obtained a different result. Also, you are talking of people in thermal neutrality. Do you think the limits would change if the people were not in neutrality? If they were already warm do you think the limits would have been different?

Dr. Olesen: Yes, I think so. There would be more discomfort from conditions which were generally too warm or too cool. The reason for gradually increasing the asymmetry, rather than randomising, was because we wanted to reach steady state within half an hour. This limits the magnitude of the differences which we could use. This may be a source of error, but I don't think it will make much difference, especially since steady state was reached within half an hour.

Mr. D.A. McIntyre: We repeated our hot ceiling experiment in a warm condition, corresponding to an average Bedford vote of five (comfortably warm), and we did not find any difference from the thermally neutral conditions in respect of tolerance to asymmetry. A ceiling temperature of 45^{o} did not produce any general discomfort.

Dr. D.P. Wyon: Could I ask both the last contributors if they think their results agree with those of Dr Banhidi? *(See the supplements to these two papers – Ed.)*

Mr. Fitt: I am surprised by one thing. McIntyre and Griffiths' subjects were in shirt sleeves (about 0.6 clo). The comfort temperature was 23^{o}, whereas Fanger would predict about 25.5^{o}. There seems to be a difference between Danish and English results.

Dr. Olesen: The clo-value of the English subjects was not measured. One could calculate back and make an estimate of it. It would appear, on this basis, that it would have been about 1 clo.

McIntyre & Griffiths (written reply): Our subjects generally wore a shirt and vest, which we estimate to have an insulation value between 0.7 and 0.8 clo. To obtain a comfort temperature of $23^{o}C$ from Fanger's comfort equation, the activity level needs to be 70 W/m^2. This is the metabolic rate listed for a person who is seated, but not inactive. There is, therefore, no reason to suppose that there is any difference between the Danish and English results.

Dr. A. Davies: Is there not a general problem in comparing environmental chamber studies with field studies? In field studies the activity of the subjects is usually greater. They can move about. But field studies also concern people in pre-existing social groups, which is not often so in chamber work, where the activities are contrived and artificial, and the social settings rather atypical. It has not yet been shown that these social factors do not influence general thermal sensation. For example, Rholes(1) had to abandon some experimental sessions with elderly women, because they got so emotionally heated playing cards that they gave over-estimates of temperature conditions. These socio-psychological factors may well be important, and they are stable in field studies in a way they cannot be in the climate chamber.

Mr. Olesen: I think that this is obviously so, but you can control activity in the climate chamber. You cannot do so in field studies.

Chairman (Dr. E. van Gunst): It is a valid point. Such chamber work must be followed up in the field

Mr. P. Jay: It is normally found that systems giving a high air temperature and a low mean radiant temperature also produce large temperature gradients. This may be the origin of the normal recommendation for slightly higher mean radiant temperature than air temperature. McIntyre and Griffiths carefully avoided any temperature gradient in their experimental work. I do not think that this type of result, valid though it may be in the chamber, will necessarily have any impact in practice until means are available of keeping the temperature gradients small when using largely convective heating.

Mr. Olesen: We expect to do work in temperature gradients soon. In this way we hope to build up comprehensive information.

Mr. McIntyre: If people dislike warm air systems, we wish to find out why. If it is due to temperature stratification, we need to look at that. The work we have done indicates that you cannot eliminate the warm air system simply because of its low radiant temperature.

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