RADIANT SLAB COOLING: A FIELD STUDY OF OCCUPANT THERMAL COMFORT

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ABSTRACT

This paper introduces a field study of thermal comfort with radiant slab cooling systems. The study combined field measurements and questionnaires based on the ASHRAE RP-921 project protocol. The observed occupant mean thermal votes with a radiant cooling were generally consistent with the PMV model. Detailed assessment indicates that personal, contextual and psychological factors did not affect occupant thermal votes at the time of this survey. The main advantage of radiant cooling for thermal comfort was found to be reduced local thermal discomfort with reduced vertical air temperature difference as well as reduced draft rate. The survey results also reveal that about 14-22% of participants in the survey reported local cold discomfort in the arm-hand and the leg-foot regions.

INTRODUCTION

The main purpose of environmental control is to provide comfortable environments for building occupants. Thermal comfort methods to predict or evaluate whether a thermal environment is comfortable have been developed based on thermal comfort research. At the same time, thermal comfort standards are directly related to building energy use. The smaller the comfort range, the more energy is required to control thermal conditions. The selected design criteria for thermal comfort will therefore affect the design of buildings and their environmental control systems (Brager and de Dear 2000; ASHRAE 2004).

To assess whether or not an indoor thermal environment is comfortable, normally two approaches are applied: 1) physical measurements, and 2) surveys involving questionnaires.

Physical measurements of indoor thermal parameters and comparisons to existing thermal comfort standards such as ASHRAE 55 (ASHRAE 2004) or ISO 7730 (ISO 1994), make it possible to determine whether the thermal variables are within the comfort range (ASHRAE 2004).

In a field survey, occupants are asked one or more questions, which can range from a single, direct question about whether or not the occupant is comfortable, to an extensive questionnaire (McIntyre 1980). Questionnaires may include subjective measures of occupant clothing, level of activity, occupant's votes on a rating scale (ASHRAE scale or Bedford scale) and some background information (McIntyre 1980). The ASHRAE scale has the following categories (with numerical representation): +3, hot; +2, warm; +1, slightly warm; 0, neutral; –1, slightly cool; –2, cool; and –3, cold (ASHRAE 2001).

The fundamental objective of thermal comfort research is to deal with real-life thermal comfort issues. The prevailing thermal comfort standards are based on steady-state heat balance theory and most data are derived from climate chamber experiments using conventional air-conditioning systems (Loveday *et al.* 1998; Brager and de Dear 2000; de Dear 2004). The applicability of these standards for "real-world" building occupants may be limited (de Dear 2004), especially for buildings with natural ventilation, hybrid ventilation or radiant cooling.

In recent years, hydronic radiant cooling has been increasingly applied in western European countries, for its potential to improve thermal comfort and increase energy efficiency (e.g. Imanari *et al*. 1999; Watson and Chapman 2002; Mumma 2002: 223).

Radiant heat exchange between the human body and its surroundings has a significant influence on thermal comfort, and the mean radiant temperature (MRT) is an important factor in assessing this exchange. As the conventional mixed-air systems cool building spaces only through convection (Feustel and Stetiu 1995), air temperature is considered as the main factor in thermal condition parameters and the importance of mean radiant temperature is overlooked. The radiant cooling provides thermal comfort by controlling surface temperatures instead of indoor air temperature. With radiant cooling, heat rejection by radiation increases and perspiration decreases relative to conventional mixed-air systems (Mumma 2002).

Some authors (e.g. Brunk 1993; Mumma 2002) argue that the space operative temperature with radiant cooling systems could be perceived about 2 ^{o}C lower than with mixed-air systems. This assertion should be tested by empirical investigation. Therefore, a field study was conducted to examine the thermal comfort conditions with radiant cooling in the real thermal environments. The main objective of this field study was to explore predicted mean votes (PMV) for occupant thermal comfort votes with radiant cooling and the applicability of ISO 7730 or ASHRAE 55-2004 in a radiantly cooled environment.

THERMAL COMFORT STUDY

Research methods

According to the central limit theorem in statistics, a minimum sample size of 30 is required (Kenkel 1989). de Dear (2005), suggested a minimum sample size of 40 participants for a field study of thermal comfort to account for the inter- and intra-individual difference. From a statistical point of view, increasing the number of participants provides more generalizable results. The reliability of the survey results also depends on the quality of individual responses (Robson 1993). In this research, a total of 82 participants (58 in summer and 58 in winter) was included in the two rounds of survey. Among them, 34 occupants participated in both the summer and winter rounds.

In order to minimize factors such as effects of operable windows on occupant thermal sensations, only the subjects working in the core zones were selected. In these core zones, the thermal conditions are relatively stable as the indoor temperature variations in the core zones are quite small. In addition, in these core zones, occupants generally had no or only slight control over their environment.

The thermal comfort survey adopted the method of combining field measurements and subjective questionnaires, similar to ASHRAE RP-921 (Cena *et al.* 1998). An additional step was added. The respondents' checklists of clothing were compared with observations. If differences were found, then the investigator would follow-up with respondents and ask them to correct their checklists if discrepancies were noticed. In the thermal comfort questionnaire, a question was added asking participants if they felt warmer or cooler in specific body areas.

Description of indoor thermal conditions

The measured air temperatures at work stations generally ranged from 20.6 to 24 ^{o}C with an average of 22.3 ^{o}C for both summer and winter seasons. The operative temperatures varied between 20.3 and 23.6 ^{o}C with an average value of around 22 ^{o}C in winter and summer. The summer average relative humidity was about 36% and winter mean relative humidity was around 11%. The average air velocity was about 0.06 m/s for both seasons.

The standard deviations of temperatures (around 0.7-0.8 ^{o}C) in summer and winter reveal that the interior spaces of the ICT Building had a small transverse variation that varied little over time. With the operative temperature around 22 ^{o}C in the summer, the average indoor temperature was on the cool side, according to ASHRAE 55 standard.

By comparing the thermal variables collected at 0.6 m level and the data averaged from three heights (0.1m, 0.6m and 1.1m), it was found that the difference between two sets of data were negligible. The results indicate that the research could use the data collected at the 0.6 m level for calculating thermal comfort indices.

Clothing insulation and metabolic rates

The intrinsic clothing insulation was calculated from respondents' clothing checklists according to the ISO 7730 (ISO 1994) and ASHRAE 55 (ASHRAE 2004). On average, the clothing insulation value was 0.55 *clo* (St.Dev.=0.16 *clo*) in summer and 0.73 *clo* (St.Dev.=0.18 *clo*) in winter. The estimated chair insulation was 0.15 *clo* (Cena and de Dear 1998), increasing respondents' insulation values to about 0.7 *clo* in summer and 0.9 *clo* in winter.

The metabolic rate estimate was based on respondents' checklists of activities during the hour prior to filling out the thermal comfort questionnaire. In summer and winter, the average metabolic rate was about 1.18 *met* (St.Dev.=0.15 *met*), calculated according to ASHRAE 55 (ASHRAE 2004).

Calculated overall comfort indices

In summer, the average PMV was -0.53, indicating significantly cooler-than-neutral conditions (-0.9 to -0.5) but only marginally exceeded the comfort range described in ASHRAE 55 (-0.5<PMV<0.5) (ASHRAE 2004). The average PMV in the winter was -0.32, also on the cool side but within the comfort range. The calculated predicted percentage PPD value projected that the proportion of participants who would be dissatisfied with the overall thermal conditions would be around 16% in summer and around 10% in winter.

Calculated secondary comfort indices

The predicted mean draft rates in summer and winter were lower than 4%, indicating that only fewer than 4%

of participants would have draft risk. This low draft rate was the effect of low air velocities (mean value 0.06 ±0.03 m/s) encountered in the interior spaces of the ICT Building.

In general, the average vertical air temperature difference (0.1 to 1.1m) was lower than 0.5 ^{o}C in both summer and winter seasons. The maximum vertical air temperature difference was withing 1 ^{o}C in summer and 2 ^{o}C in winter. Thus fewer than 2% of participants in both seasons would be dissatisfied with the vertical temperature difference, according to ASHRAE 55 standard.

The floor surface temperatures ranged from 19 to 22.8 ^{o}C in summer and 19.4 to 23.8 ^{o}C in winter, within the range of 19 to 29 ^{o}C prescribed in ASHRAE 55 (ASHRAE 2004). The average floor surface was about 21 ^{o}C and the standard deviation was about 1 ^{o}C in both seasons. Around 8% of participants would be dissatisfied with the floor surface temperature (ASHRAE 2004), although there would always be about 6% dissatisfied with floor surface temperature due to individual differences.

The measurement of surface temperatures in six directions revealed the average temperature differences between the ceiling and floor were about 0.5 and 0.8 ^{o}C in summer and winter, respectively. In general, the biggest temperature difference occurred between the wall with the highest temperature and the floor. The average temperature difference was about 2 ^{o}C in both seasons and maximum temperature differences were about 3.5 ^{o}C and 3.8 ^{o}C in summer and winter, respectively. With the small temperature differences among surfaces, the radiant temperature asymmetry should be within 5 ^{o}C. Taking these facts into account, the ratio of participants dissatisfied with radiant temperature asymmetry should be less than 5% and possibly about zero.

ANALYSIS OF RESULTS

Comparing PMV and AMV discrepancy

PMV can only be used to predict the mean thermal sensation of a large group of people rather than individual votes. By subtracting the actual mean vote (AMV) of participants from corresponding PMV for each survey instance, an unbiased but low precision estimation of the discrepancy between PMV and AMV can be obtained. (Humphreys *et al.* 2002).

The mean values of summer, winter and combined PMV-AMV discrepancies were within the range of ± 0.1, and close to zero (Table 1). The standard deviation values are close to one scale unit and within the standard deviation of one scale unit for inter- and intra-individual difference of thermal sensation (McIntyre 1980).

Table 1: PMV-AMV discrepancies

Season		**Summer**	**Winter**	**Combined**
PMV-AMV	Mean	0.06	-0.09	-0.02
	St.Dev.	0.92	0.75	0.84
	No.	58	58	116

The histogram distribution of all PMV-AMV discrepancy data are illustrated in Figure 1. The distribution of PMV-AMV discrepancies is closely normal with maximum discrepancy about ± 2.5 scale units of thermal sensation.

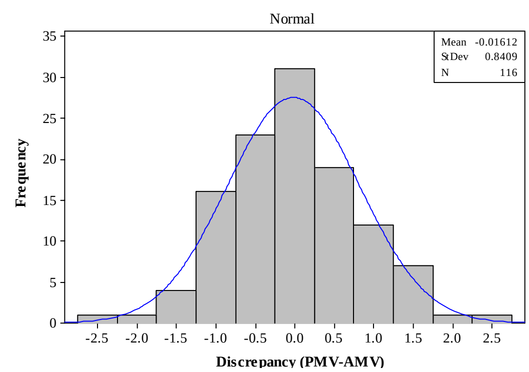

Figure 1: Histogram of PMV-AMV discrepancies

The range of the mean PMV-AMV discrepancy indicates the success of the PMV model in predicting mean thermal sensation in that specific circumstance (Humphreys *et al.* 2002). If the 2 ^{o}C operative temperature difference stated in some literature (e.g. Brunk 1993: 480; Mumma 2002) did exist, then under the same operative temperature, the mean discrepancy of thermal sensations with radiant cooling and mixed-air system would have a magnitude of 0.67 scale units, since generally a 3 ^{o}C difference in temperature has the impact of one scale unit change in thermal sensation (ASHRAE 2001). Humphreys *et al.* (2002) suggested using ± 0.25 scale units of thermal sensation as the indication of whether or not the PMV model has significant bias in predicting the actual mean thermal sensation.

In this investigation, the mean difference between PMV and AMV was less than 0.1 scale units (Table 1). The magnitude is not only significantly less than 0.67 scale units but also less than 0.25 scale units. This indicates that the 2 ^{o}C operative temperature difference in radiant-cooling and mixed-air systems may not exist. Using the data as a whole, the PMV model had no significant bias in predicting actual mean vote with radiant cooling in both winter and summer.

As shown in Humphreys *et al*. (2002) analysis, the PMV model can predict the actual mean thermal sensation but the accuracy of the estimate declines as the temperature deviates from the center of the comfort envelope.

To further investigate the PMV model in predicting AMV regard to different temperatures, the data were binned into 0.5 ^{o}C operative temperature intervals.

As shown in Figure 2, the magnitudes of PMV-AMV discrepancies vary between around 0.3 to -0.3 within the temperature range of 20 to 24 ^{o}C. During the 20.5, 21.5 and 23.5 ^{o}C temperature intervals, the discrepancies of PMV-AMV marginally exceed the magnitude of ± 0.25 scale units. However, these three intervals all included fewer than 16 respondents, the minimum number of respondents in one exposure of climate chamber research to account for individual differences (de Dear 2004; Loveday *et al.* 1998). From the available data that exceed 16 respondents, in general the magnitude of PMV-AMV discrepancy is within the range of ± 0.25 scale units. In addition, if radiant cooling really has the net effect of being perceived as cooler under than same operative temperature (Brunk 1993), then the PMV-AMV discrepancies in all temperature intervals should have all positive values.

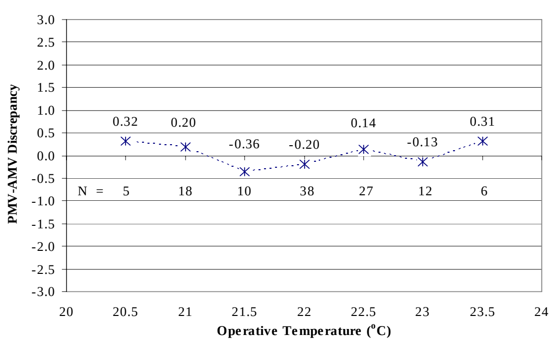

Figure 2: Binned PMV-AMV discrepancies

Comparing predicted and actual dissatisfaction

As the PMV model can only be used for predicting whole-body mean thermal sensation of a large group of people, the satisfaction of or acceptability to thermal environments is affected by secondary local thermal conditions as well.

ASHRAE 55 standard (ASHRAE 2004) was designed to provide 80% acceptability of thermal environment based on 10% dissatisfaction for general (whole body) thermal comfort and additional 10% dissatisfaction resulting from local discomfort. However, it is unclear whether dissatisfaction from general discomfort is additive to dissatisfaction resulting from local discomfort or they combine in some other way (de Dear 2004).

As this research adopted the continuous scale based on the ASHRAE 7-point scale, generally the thermal sensations voted lower than -1.5 or higher than 1.5 were treated as "dissatisfied with thermal environments" (McIntyre 1980). In summer about 8 respondents out of 58, about 14% voted thermal sensation beyond the ± 1.5 interval and in winter 6 votes out of 58 were outside this interval. At the same time, participants were asked about the acceptability of their thermal environments. In both seasons, 5 participants, about 9% voted their thermal environments "unacceptable" (Table 2). However, as thermal acceptability is more related to psychological factors and thus more easily biased than the thermal sensation votes, the approach using thermal sensation votes is more widely accepted than the method of thermal acceptability (McIntyre 1980).

By comparing the predicted percentage of dissatisfied (PPD) and actual dissatisfaction rate, it was found that the actual dissatisfaction rates in both summer and winter were very close to the calculated PPD. The unacceptability rates to thermal environments were slightly lower.

Table 2: PPD, Actual dissatisfaction and unacceptability rate

Season	**Summer**	**Winter**
Sample size	58	58
PPD	15.6%	10.1%
Actual dissatisfaction rate	13.8%	10.3%
Unacceptability rate	8.6%	8.6%

From comparison of the data, it appears that almost all respondents dissatisfied with their thermal environments resulted from general discomfort with overall thermal conditions, as the calculated draft rate (less than 4%), vertical air temperature difference (less than 2%), radiant temperature asymmetry (possibly around 0%) are far lower than the required upper limitation in standard (ASHRAE 2004). Even though the calculated values showed that around 8% of participants may be dissatisfied with local foot comfort at an average floor temperaure around 21 ^{o}C, the thermal sensation at the feet does not affect the overall thermal sensation much, unless conditions were severe (Zhang 2003).

Local discomfort

In summer, 13 participants out of 58, about 22% voted their arms or hands feeling “cooler and uncomfortable”; 8 respondents, about 14% voted their feet or legs “cooler and uncomfortable”. In winter, 10 participants out of 58, about 17% voted their arms and hands feeling “cooler and uncomfortable”; about 17% of participants voted their feet or legs “cooler and uncomfortable”. Although in summer 7 out of the 13 respondents voting “cooler and uncomfortable” for the arm region were wearing short-sleeve shirt at the time of survey, only 1 out of 10 respondents was wearing short-sleeve shirt during the winter survey. Moreover, in the winter survey, 4 out of 10 respondents were in the overall neutral or warmer-than-neutral conditions when they reported “cooler and discomfort” in the arm/hand region. The reason for this requires further investigation.

Analysis of the impact of personal, contextual and psychological factors

The comparison between PMV and AMV shows free of significant discrepancy for the temperature range 20 ^{o}C to 24 ^{o}C. An important aspect in field comfort research is to analyze the impact of personal, contextual and psychological factors on occupant thermal sensations. With the SPSS program (2004), the impact of these factors was assessed in three methods.

1) General overall correlation analysis (used in ASHRAE RP-821)

Factors from “background questionnaire” such as job satisfaction, work area satisfaction, health characteristics, environmental sensitivity, perceived personal control, lighting satisfaction and the satisfaction with sounds were compared with the actual thermal votes through correlation analysis. The data as a whole indicate that the actual warmth votes at the time of survey were free of significant effects from these factors.

2) Group correlation analysis (improved from ASHRAE RP-821)

Assuming these factors influence actual thermal votes, in the “cooler-than-neutral” (AMV<0) group, factors such as job satisfaction, work area satisfaction, personal control, lighting satisfaction and sound satisfaction would correlate positively with actual warmth votes (correlation coefficient r>0.25); in the “neutral” and “warmer-than-neutral” group these factors would correlate negatively with actual warmth votes (correlation coefficient r <-0.25). On the other hand, factors like health characteristics and environmental sensitivity would correlate negatively with actual warmth votes in group of “cooler-than-neutral” and positively in the other group.

The correlation analysis of the two split groups shows the job satisfaction was not related to the actual mean vote at the time of survey. The scatterplot in Figure 3 below also shows that there was no direct correlation between job satisfaction and actual thermal votes.

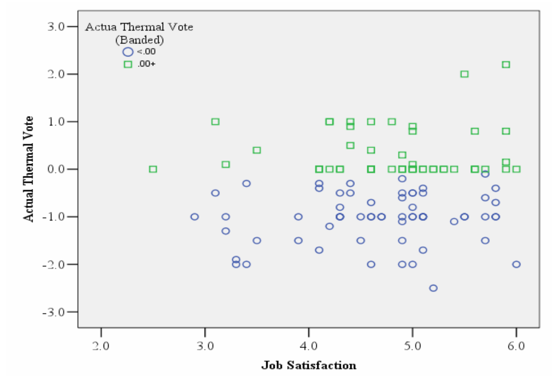

Figure 3: Scatter distribution of actual thermal votes over job satisfaction votes

Similarly, assessment of the relationship between actual thermal votes and the following factors: work area satisfaction, personal control, lighting satisfaction, sound satisfaction, health characteristics and environmental sensitivity indicated that actual thermal votes at the time of survey had no dependency on these factors (absolute value of correlation coefficient | r | < 0.25).

3) Crosstabs analysis (used in ASHRAE RP-921)

Job satisfaction effects: An index of job satisfaction was created by averaging the scores on the 15 job satisfaction rating scales in the background questionnaire. The mean value of job satisfaction was 4.3. Of the 115 votes (one participant refused the job satisfaction voting), 52 participants scored below-average job satisfaction and 63 participants reported above-average job satisfaction. Among the 52 below-average participants, 6 participants, about 11.5% were dissatisfied with their thermal environments at the time of survey (the absolute value of AMV>1.5), while 8 out 63, about 12.7% in the above-average group were dissatisfied with thermal environment. Chi square on 1 degree of freedom (d.f.) = 0.036, p=0.85 indicates that thermal votes at the time of survey were independent of job satisfaction or vice versa.

Work area satisfaction effects: Similar to the above analysis of job satisfaction, an index of thermal area satisfaction was created by averaging the scores on the 11 work area satisfaction rating scales in the background questionnaire. The mean rating of work area satisfaction was 4.1. Of all the 116 votes, 50 reported below-average work area satisfaction; and 6 out of 50, about 12% were dissatisfied with thermal environments at the time of survey. 8/66, about 12.1% were dissatisfied with thermal environments and above-average work area satisfaction. Chi square on 1 d.f. =0.0004, p=0.98 indicates no link between work area satisfaction and thermal votes at the time of survey.

Personal control effects: The mean rating of personal control over thermal environments was 1.4. Of the 116 votes, 83 reported below-average personal control (voted no control); among them, 13 votes, about 13.2% were dissatisfied with thermal environments at the time of survey. While 3/33, about 9.1% with above-average control (voted slightly control to complete control) were dissatisfied with their thermal environments. Chi square on 1 d.f.= 0.385, p= 0.53 indicates that personal control had no direct correlation with actual thermal sensations at the time of survey in this study.

Health characteristics effects: An index of health characteristics was created by summing the scores on the 10 health symptoms in the background questionnaire. The average health condition rating was 2.3. Within 116 votes, 53 reported worse than average health and 63 reported better than average. 7/53, about 13.2% were dissatisfied with thermal environments at the time of survey; while 7/63, about 11.1% were dissatisfied with thermal environments. Chi square on 1 d.f.=0.12, p=0.73 shows no link between health characteristics and specific thermal sensations at the time of survey.

Environmental sensitivity effects: An index of environmental sensitivity was also created by summing the scores on the 8 sensitivity questions. The average environmental sensitivity was 4.3. Of all the 116 votes, 52 votes were below average and 64 reported above average sensitivity. 8 out of 52 votes, around 15.4% were dissatisfied with thermal environments occurring at the time of survey; while 6 out of 64 votes, about 9.4% were dissatisfied in the above average group. Chi square on 1 d.f.=0.98, p=0.32 indicates no link between environmental sensitivity and participant thermal votes at the time of survey.

Gender effects: Another important aspect assessed in this research was gender effect. Only 38% of participants were female, as they constituted a smaller fraction of occupants. The possible impact of gender on actual thermal sensations was evaluated by crosstabs analysis. Of the 116 votes, 7/74 male participants, about 9.5% were dissatisfied with their thermal environments at the time of survey (the absolute value of AMV>1.5); 7/42 female participants, about 16.7% were dissatisfied with thermal environment. The crosstabs analysis produced an insignificant value: Chi square on 1 d.f. =1.3, p=0.25, indicating that the actual thermal votes and gender are unrelated.

Acclimatization effects: Extensive exposure to air conditioning may diminish physiological and psychological acclimatization (Donnini *et al.* 1997). In summer, 17 participants, about 29%, were using air-conditioning at home or in the car. Among them, 16 participants were using car air-conditioning. Of the summer 58 votes, 4 out of 17 participants, about 23.5%, in the using air-conditioning group were dissatisfied with concurring thermal conditions. Also, 4 out of 41 participants in the group of “not using air conditioning”, about 9.8% were dissatisfied. Crosstabs analysis with Chi square on 1 d.f.=1.9, p=0.17, indicates lack of significant influence for the effect of using air conditioning on thermal sensations at the time of survey.

Combining all the analyses above together, we may conclude that statistically the actual thermal sensations at the time of survey were free of significant correlation with these factors in this study.

CONCLUSIONS

Through combined measurement and survey of 82 respondents in summer and winter, this study found that the PMV model can correctly predict the actual mean vote of a large group of people in the temperature range of 20 ^{o}C to 24 ^{o}C. The findings failed to support the purported 2 ^{o}C temperature advantage of radiant cooling systems over conventional mixed-air systems. Compared to conventional mixed-air systems, the main advantages with radiant cooling in terms of occupant thermal comfort are reduced local discomfort from vertical air temperature difference and draft rate, instead of general discomfort. In this research, about 14-22% participants reported the same level of local discomfort at the arm/hand region as that at the leg/foot region. The statistical analysis results reveals that actual warmth votes at the time of survey were free of effects by personal, contextual and psychological factors.

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