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A field study of occupant thermal comfort and thermal environments with radiant slab cooling

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Abstract

This paper presents the findings of a field study of occupant thermal comfort and thermal environments with a radiant slab cooling system. The study combined field measurements and questionnaires based on the ASHRAE RP-921 project protocol. A total of 116 sets of data from 82 participants were collected in summer and winter. The results reveal that occupant whole-body thermal sensations with radiant cooling were consistent with the PMV model. 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 revealed that 14–22% of participants in the study reported local cold discomfort in the arm–hand and the leg–foot regions. The results indicated that there may be lower limits on air speeds acceptable to occupants. Statistical analysis indicated that occupant thermal votes were free of significant correlation with personal, contextual and psychological factors. Suggestions to improve the questionnaire and the field survey process are offered.

Keywords: Thermal comfort; Radiant cooling; PMV; Actual thermal sensation; Local discomfort

1. Introduction

In Canada, most buildings have to be heated in winter and cooled in summer [1]. In recent years, hydronic radiant cooling, which is defined as 50% or more of energy transfer accomplished through radiation [2], has been increasingly applied in western European countries [3] due to its potential to increase energy efficiency and improve thermal comfort [4–6].

Radiant cooling systems provide 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 [6]. Some authors [7] argued that the space temperature with radiant cooling systems could be perceived as about 2 °C lower than with mixed-air systems. However, this statement should be tested by empirical investigation. A climate chamber test [8] indicates that the ISO 7730 standard is applicable to radiant cooling. Imanari et al. [4] claim more comfortable thermal conditions with radiant cooling, compared with mixed-air systems. With so little reported field research, much remains to be learned about comfort conditions with operating radiant cooling systems [3] and the factors that contribute to the improvement of thermal comfort with radiant cooling. As the prevailing thermal comfort standards are based on steady-state heat balance theory and most data are derived from experiments in climate chambers with conventional air-conditioning systems [8–10], applicability to "real-world" building occupants remains to be clarified [10].

Given this situation, a field study was conducted to examine thermal comfort conditions in a building with radiant slab cooling. The main objectives of this study were to (1) assess predicted mean votes (PMV) in determining occupant-reported thermal sensation votes with radiant cooling and the applicability of ISO 7730 [11] and

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ASHRAE 55-2004 [12] in a radiantly cooled environment, and (2) analyze the main factors affecting occupant thermal comfort with radiant cooling, including both overall and secondary comfort factors.

2. Methods

The field study was conducted in the Information and Communication Technology (ICT) Building at the University of Calgary. Completed in 2001, the ICT Building is a seven-storey 17,500 m^2 teaching and research facility. The radiant slabs provide cooling over most of the floor plates on levels 2–7. The radiant slab system provides cooling by circulating water at 16–22 °C in polyethylene pipes that are embedded in the concrete slabs. There is no insulation layer in the slabs, so the system acts as both a chilled ceiling and a chilled floor.

The thermal comfort investigation combined field measurements and occupant questionnaires. All occupants (professors, support staff and students) on floors 2–7 of the ICT Building were potential participants. In order to minimize variables such as the effect of operable windows on occupant thermal sensations, only the occupants in the interior zones were included. In these interior zones, the thermal conditions are relatively stable as the temperatures in the interior zones are independent of seasonal conditions and cooling is required year round due to internal gains.

According to the central limit theorem in statistics, a minimum sample size of 30 is required [13]. de Dear [14] suggested a minimum sample size of 40 participants for a field study of thermal comfort to account for inter- and intra-individual differences. 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 [15]. In this study, 82 participants (58 in summer and 58 in winter, with some individuals participating in both seasons) were involved in the two rounds of the survey.

2.1. Measurement of indoor climates

Thermal parameters at workstations were measured with a Dantec VIVO system for measuring operative temperature, air temperature, air velocity and relative humidity. In addition, as the floor surface temperature and radiant temperature asymmetry may affect occupant thermal sensations, the six surface temperatures in each space were also measured using an Omega OS950 handheld infrared thermometer.

2.2. Comfort and background questionnaire

The occupant questionnaire included two parts: thermal comfort and background. Following the ASHRAE RP-921 protocol [16], the thermal comfort questionnaire addressed occupant thermal sensations, acceptability of thermal environment, thermal preference, satisfaction with air movement, general comfort, activities in the previous hour, the clothing worn during the survey, and use of home and vehicle air conditioners. A question was added about thermal comfort in local body areas, in order to address local discomfort with radiant slab cooling.

ASHRAE 55 provides a discrete seven-point scale for rating thermal sensations. ASHRAE RP-921 adopted a continuous scale, allowing non-integer thermal sensation ratings [16]. A continuous thermal scale will provide reduced error in experiments dealing with small differences in thermal sensations [18]. With a continuous scale, the comfort range is interpreted as votes between -1.5 and 1.5 (the boundary between 1 and 2); while in the discrete scale the comfort range is interpreted as votes between -1 and 1 [16,18].

The background questionnaire covered demographic data, as well as contextual and psychological factors that may affect occupant thermal responses to environments. The topics included satisfaction with work area, personal comfort, personal control, job satisfaction, health characteristics and occupant environmental sensitivities. Some minor adjustments were made to the ASHRAE RP-921 background questionnaire to ‘‘aboriginal’’ under ‘‘ethinic background’’.

The field study was conducted in August 2005 for the summer assessment and from November 28 to December 15, 2005 for the winter assessment. The radiant cooling system in the ICT Building was operating during these periods.

3. Survey results

3.1. Description of questionnaire respondents

Of the 82 total participants in the two rounds of the survey, 48 individuals completed one thermal comfort questionnaire and 34 individuals completed two thermal comfort questionnaires, for a total of 116 completed questionnaires. All individuals finished one background questionnaire. A set of measurements of indoor thermal conditions was made for each workstation while the questionnaire was being completed.

Among the 82 participants, about 40% were female. The average age of participants was about 28 years with a range of 20–50 years. All participants had a high school diploma, 93% of participants held a bachelor's degree and 58% held at least one graduate degree. About 56% of participants reported an Asian ethnic background, 40% Caucasian and 4% African ethinic background. About 48% of respondents reported English as their first language. The average length of residence in cold climate regions was about 11 years. According to Cena and de Dear [16], 96% of these participants could be regarded as ‘‘naturally acclimatized’’ to the cold-dry climate of Calgary as only 4% of respondents had lived in a cold region for less than a year.