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THERMAL COMFORT ASSESSMENT IN CHILLED CEILING AND DISPLACEMENT VENTILATION ENVIRONMENTS

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ABSTRACT

The use of air-conditioning is known to be an energy-intensive solution to the problem of providing thermally comfortable conditions in buildings. This has led to the adoption of new techniques, such as displacement ventilation and chilled ceiling systems as a means for providing the cooling requirements. In addition, benefits are gained in terms of indoor air quality and comfort. However, there is a lack of information about the effect that chilled ceiling has on displacement air flow, and the corresponding implications for occupant thermal comfort.

The thermal comfort of 128 test subjects (64 male, 64 female) was then measured in a test room over a range of ceiling temperatures. Vertical radiant asymmetry was found to have an insignificant effect on thermal comfort of the seated occupants for ceiling temperatures ranges from 12 C to 22 C. However, ceiling temperature was found to have an effect on the freshness vote. Furthermore, the Fanger thermal comfort model is shown to be capable of predicting the PMV of subjects in such environments.

1. INTRODUCTION

Energy consumption in buildings is responsible for about 50% of the UK's total carbon dioxide emissions, with a similar situation prevailing in other industrialised countries. In many industrial and commercial buildings the provision of comfortable space conditions has often been achieved through the use of air-conditioning, widely recognised as being an energy-intensive solution to the problem. The emphasis is now shifting towards the design of low energy buildings and the enhancement of quality of the indoor environment for the user. Interest has therefore been grown into the adoption of low energy techniques for the conditioning of office environments, and among these is the displacement ventilation and chilled ceilings.

In displacement ventilation, full fresh air is introduced gently to a space at low level, low velocity and at a temperature lower than that of a desired zone air temperature. Density differences cause the fresh air to form a layer over the floor; the air then rises as it is warmed by heat sources in the zone, and the convective plumes generated by these sources remove heat and contaminants which are extracted at ceiling level. The system is able to provide an environment of improved air quality as compared with the mixing of air which occurs in conventional HVAC systems for the same air flow rate conditions; also, the same heat loads can be removed for a supply air temperature of typically 19 C as compared with supply temperature of 13 C in HVAC system. As a result of thermal comfort limitations, namely that the vertical air temperature gradient should be less than 3 C per metre (ISO 7730, 1994 [1]), a displacement ventilation is limited to removing a convective load up to 25 Wm^{-2} of floor area (Sandberg and Blomqvist, 1989 [2]). However, heat gains in offices frequently exceed this figure and so it becomes necessary to install an additional cooling mechanism, such as chilled ceiling.

In chilled ceiling system, cold water flows through pipework which is bonded to a ceiling tiles, producing a typical ceiling tile surface temperature in the range of 16-19 C. Chilled ceilings can remove heat loads of up to $100Wm^{-2}$ of floor area mainly by radiation, and are considered to enhance the thermal comfort sensation of occupants. When combined with displacement ventilation, Taki et al (1996) [3] have shown that this could cause deterioration in air quality as a result of a diminished displacement flow pattern. However, there is at present a lack of information about the performance of the combined chilled ceiling/ displacement ventilation system and in particular, the implications for thermal comfort in such environments. A full-scale office has been constructed to determine the design conditions necessary for occupant thermal comfort in such environments. The work is still continuing, but here we report findings to date on the following:

i) the effect of ceiling temperatures on freshness votes,
ii) the validity of the Fanger model for predicting overall thermal comfort in chilled ceiling/ displacement ventilation environment, and
iii) the comfort limits for the vertical radiant asymmetry.

2. THE EXPERIMENTAL FACILITY

This has already been described in Taki et al (1996) [3] but is repeated here for convenience. A test room has been constructed to act as an office environment, employing a chilled ceiling and displacement ventilation system (Figure 1). It is a light weight room 5.4m long, 3m wide and 2.8m high, and its four wall are clad with frenger panels offering control of the wall surface temperatures. The chilled ceiling and displacement ventilation system is comprised of commercially available units. The chilled has a 90% active area and consists of 6 individual circuits connected in parallel. Each circuit, in turn, is comprised of 4 or 5 chilled panels connected in series, and the area of each circuit is approximately $2.5m^2$. The circuit can be activated individually or collectively. Displacement ventilation is provided by a semi-cylindrical wall-mounted diffuser fitted at one end of the room; this is supplied with fresh air which can be tempered and humidified prior to entry into the space. The room is equipped with a window which overlooks the external environment, so as to preserve the impression of a normal office. However, the window is comprised of seven layers of glass, providing insulation from the external environment, and thus minimising temperature differences between wall and glass surfaces; this enhanced by extending the water flow network to include the window itself. The test room is carpeted and furnished to a normal office standard, and can either be equipped with thermal dummies to simulate human sources (as used in the tests on displacement flow/ chilled ceiling interaction) or can be used for thermal comfort tests involving human subjects. All environmental parameters within the room are controllable; these include supply air flow rate, air temperature, relative humidity, mean radiant temperature and the surface temperature of the chilled ceiling. All surface temperatures in the room are measured using Type T copper/constantan thermocouples to a resolution of $\pm$0.2C. The vertical air temperature profile in the room is recorded using eight radiation-shielded thermocouples (Type T) mounted on a column. The mean radiant temperature, the mean air velocity and the turbulence intensity are measured at three heights (0.1m, 0.6m, 1.1m) above the floor using a Type 1213 Bruel and Kjaer Indoor Climate Analyser. All environmental parameters were logged every 5 seconds and average values were calculated every 5 minutes.

3. EXPERIMENTAL FINDINGS

3.1 Applicability of ISO 7730

This part of the work is concerned with determining whether the existing comfort standard ISO 7730 (1994) [1] can be used for the prediction of thermal comfort in chilled ceiling/ displacement ventilation environments, conditions which are significantly different from those which prevailed during the development of the Fanger comfort model and upon which the standard is based. A total of 128 test subjects (64 males, 64 females), in the age range 21-60 years, took part in the experiment. The test room was furnished so as to provide four work places, each with a personal computer. Subjects were admitted to the test room in groups of four (2 males, 2 females) to carry out sedentary office tasks for a period of three hours. They were not allowed to move around inside the room, thus keeping their metabolic rate to the estimated value of 70 Wm^{-2} (1.2 met). The subjects wore typical office clothing provided by the experimenters, which consisted of: male- long sleeve white cotton shirt and neck tie, mixed fibre trousers, cotton socks; female- long sleeve white shirt (same type as males), mixed fibre knee-length skirt, 15 denier tights; subject wore 'office type' shoes (no sandals or training shoes). The clo value of both clothing ensembles was estimated almost the same at 0.75 clo. Four values of chilled ceiling surface temperature were selected for investigation (14, 16, 18 and 21C), at two levels of relative humidity ('medium' and 'low' corresponding to approximately 50% rh and 25% rh, respectively) for a fixed air flow rate of 3.9 air changes per hour and at a constant supply temperature of 19C. Each set of environmental conditions was experienced by a total of 16 subjects (8 males, 8 females). Subjects were asked to complete a thermal comfort questionnaire at 15 minutes intervals throughout the 3-hour test, the data from the last 45 minutes being used in the analysis. The actual mean votes (AMV) of the subjects were then determined. Measurements of mean radiant temperature and mean air velocity were taken near the subjects at three heights (0.1m, 0.6m and 1.1m) above the floor at regular intervals during the test session. These data, together with readings of air temperatures and relative humidity were used to calculate values for the predicted mean votes (PMV) of the subjects using the Fanger model as presented in ISO 7730 [1].

Figures 2 and 3 show the comparison of PMV and AMV at low and medium relative humidities, respectively. Note that each experiment point is the average of 16 subjects' responses. For both low and medium relative humidity levels, it can be seen that there is a very good agreement between PMV and AMV values across the range of ceiling temperatures investigated. This shows that for the conditions tested (which are very typical design conditions), Fanger's model in the form of ISO Standard 7730 (1994) [1] is valid for predicting the thermal comfort of sedentary occupants performing office-type tasks in chilled ceiling/ displacement ventilation environments.

3.2 Radiant Asymmetry Effects

Radiant temperature asymmetry is the difference between the plane radiant temperature of the two opposite sides of a small plane element. A further set of experiments were undertaken to determine the effect of such vertical radiant asymmetry on thermal comfort, and specifically whether this should led to the imposition of a design limit on ceiling temperature. Female subjects only were asked to take part in these experiments because our preceding work had shown that the females were generally more sensitive than the males to these thermal environments. Eight subjects, tested individually and wearing the clothing ensemble described previously, carried out sedentary office-type work with thermal dummies taking the place of the other human subjects. Ceiling temperatures of 22, 18, 14 and 12C were investigated over a 3-hour period, the PMV for each condition being maintained at a calculated value of 'neutral' (as estimated from ISO 7730) by making small adjustments to the four wall (thus effecting room mean radiant temperature). In this way, any departure from neutrality of the subject's AMV would be the of radiant asymmetry only. During the first 60 minutes the ceiling temperature was at 22C; in the following three 40-minute periods the subject was exposed to 18, 14 and 12C respectively. The subject completed five sets of thermal comfort questionnaires every 5 minutes over the last 20 minutes of each period.

The results are shown in Figure 4, where it can be seen that the vertical radiant temperature experienced within a typical chilled ceiling/ displacement ventilation has an insignificant effect on the AMV of the test subjects. This is in agreement with findings obtained by Fanger et al (1985) [4] for conventional environments.

3.3 Sensation of Freshness

The above eight female subjects were also completed a five point freshness scale. The results are shown in Figure 5, where it can be seen that the sensation of freshness can be associated with a cold surface (while PMV=0). The mean freshness vote increases when the ceiling temperatures decreases. However, further research is required to investigate this relationship.

4. CONCLUSIONS

Experiments concerned with human thermal comfort have been conducted on a typically-designed chilled ceiling/ displacement ventilation environment. For those conditions tested, the following conclusions may be drawn:

i) ISO Standard 7730 (1994) is valid for predicting the thermal comfort of sedentary occupants performing office-type tasks in such environments.
ii) The radiant asymmetry experienced within a typical chilled ceiling/ displacement ventilation environment does not significantly affect the thermal comfort of the seated occupants.
iii) Judgement about freshness can be associated with the ceiling surface temperature. It seems likely, based on the freshness scale, that the people prefer low ceiling temperatures. This trend appears to show a relationship between the sensation of freshness, and either the radiant asymmetry or downward current of cold air. Further experimental work is required to support the above claims.

ACKNOWLEDGEMENTS

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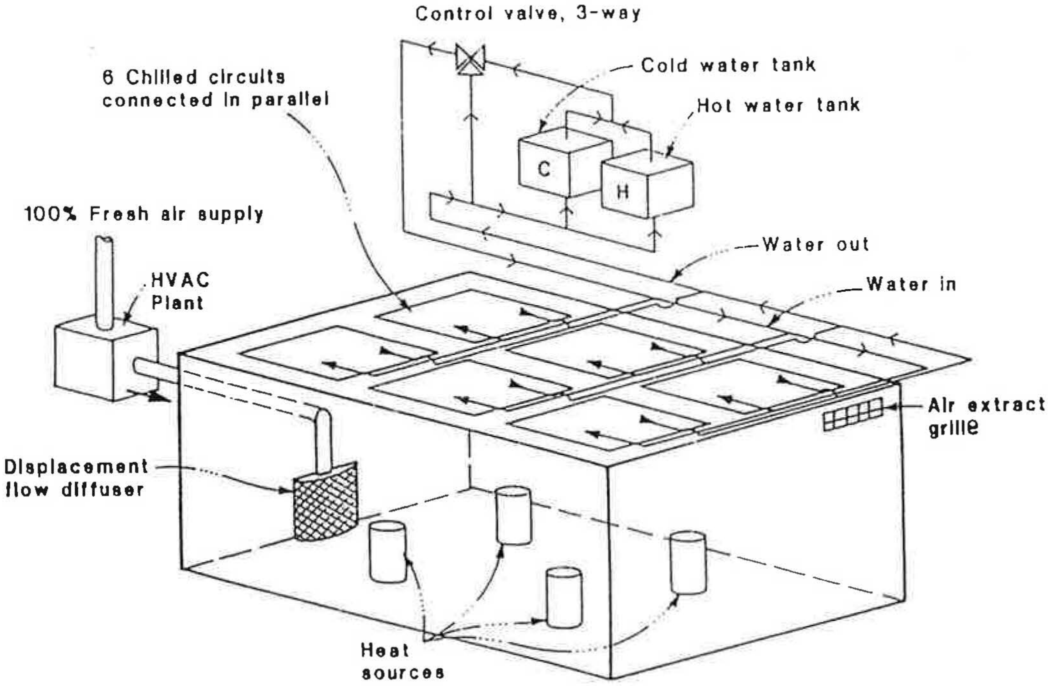

Figure 1: Schematic diagram of the test room

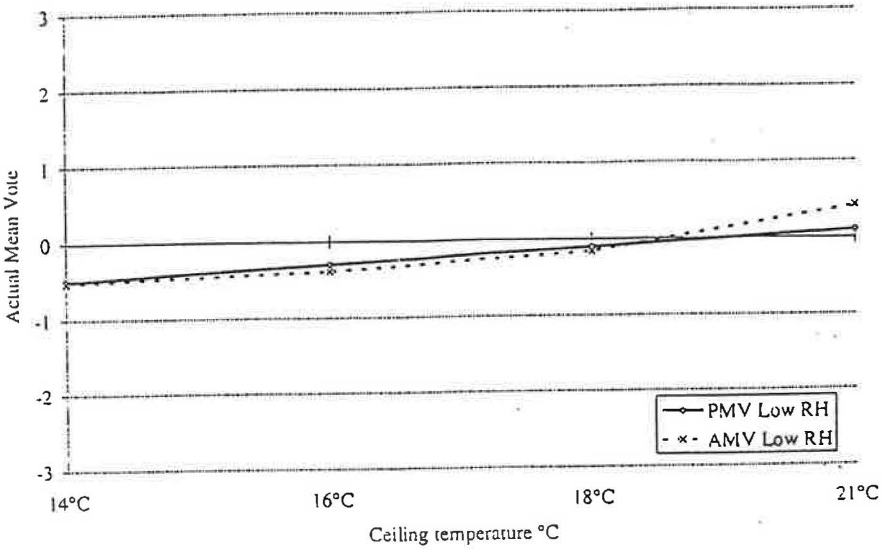

Figure 2: Comparison of AMV and PMV as a function of ceiling temperature, at low relative humidity, (N=16 per condition)

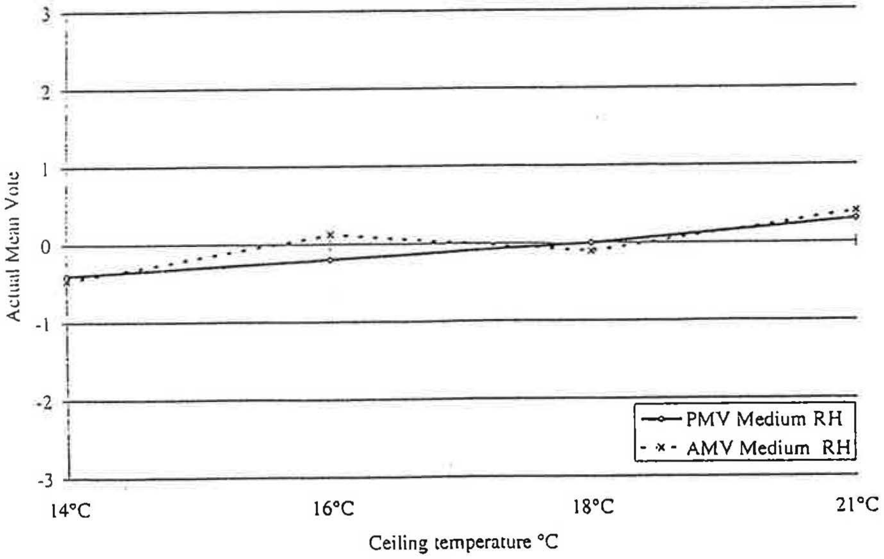

Figure 3: Comparison of AMV and PMV as a function of ceiling temperature, at medium relative humidity, (N=16 per condition)

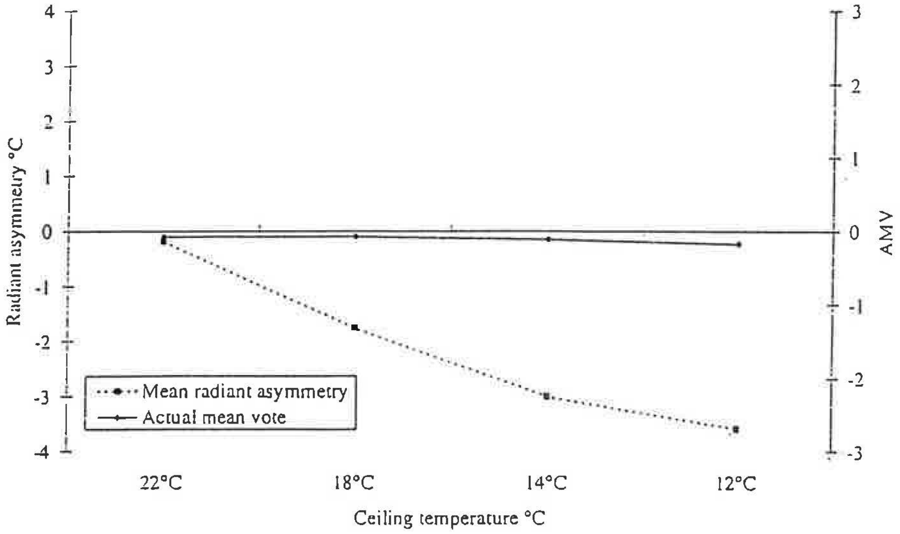

Figure 4: Effect of vertical radiant asymmetry on AMV for four ceiling temperatures

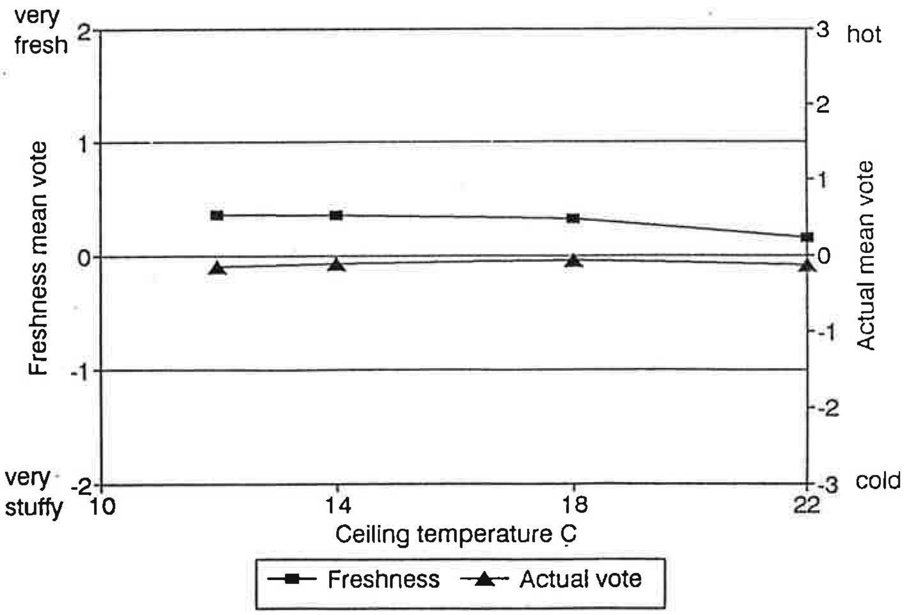

Figure 5: Comparison of AMV with freshness as a function of ceiling temperatures