Investigation of Combined Effects for the Modelling of Thermal Comfort Conditions in Buildings

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Abstract: - The purpose of HVAC appliances is to provide a comfortable environment and set the conditions for efficient work. The enhancement of buildings' energy performance puts emphasis on meeting the comfort requirements indoors, as the acceptable environments have to be provided from less energy. The comfort of the occupant is determined by the heat exchange between his body and his indoor environment. There are four local discomfort parameters that may cause discomfort on certain body parts even if whole body thermal comfort conditions are met. To help the modelling of thermal comfort conditions in buildings, on one hand we investigated, through human subject experiments, the combined effect of two discomfort parameters that are simultaneously present in the indoor space. Another modelling method is introduced in the second part of the paper where we show the results of CFD modelling of possible discomfort caused by natural ventilation required for air supply of gas appliances.

Key-Words: - Air supply, CFD method, Numerical modelling, Human subject experiment, Local discomfort

1 Introduction

The purpose of HVAC appliances, along with the construction of the building, the activity and clothing of occupants, is to provide a comfortable environment and set the conditions for efficient work. The appliances have to provide this by using less energy and emitting less pollutants to the environment.

In Europe, the energy demand of building operation takes 40% of the primary energy use. As a result, EU has put emphasis on reducing the energy use of buildings, and set requirements that member countries have to accomplish [1]. The basic principle is that energy consumption should be reduced while maintaining the desired indoor comfort. This principle requires further investigation and modelling of comfort conditions.

2 Problem formulation

Based on the results of earlier investigations, especially those of Fanger's, the comfort parameters that affect the comfort and efficiency in the indoor environment are the following:

- the temperature and distribution of air indoors,
- the mean radiant temperature of the building envelope's surfaces,
- the relative velocity,
- the partial pressure of water vapor in the air, and relative humidity of air,
- metabolic heat produced by the human body that has a specific activity level,
- the insulation of clothing,
- indoor air quality [2].

For thermal comfort the base of the sizing method is given with PMV-PPD, where
PMV – Predicted Mean Vote,
PPD – Predicted Percentage of Dissatisfied [2].

According to the standard that is applied for the determination of comfort conditions [2], four local discomfort parameters exist that may cause discomfort on certain body parts even if whole body thermal comfort conditions are met:

– Radiant temperature asymmetry,
– Warm and cold floors,
– Vertical air temperature difference,
– Draught.

Based on the range of PMV value and the predicted percentage of dissatisfied and due to local discomfort parameters, indoor spaces are categorized by the standard into category A, B and C. The newer standard that aims at increasing the energy efficiency of buildings [3] applies four categories and gives the PMV-PPD values for those.

Even though the sizing diagrams and values are results of extensive laboratory investigations, they do not apply to cases when the different local discomfort parameters are simultaneously present in the indoor space, thus we carried out experiments and modelling for these cases.

Until recently only very few research studies dealt with multiple short-term exposures, e.g. combined effect of temperature, indoor air quality and noise were studied by Balazova et al. [4] and Clausen et al. [5]. Berglund et al. [6] evaluated the subjective human response to low-level air currents and asymmetric radiation. Olesen et al. [7] and Toftum [8] outlined in their papers the need for further investigations regarding combined effects of local discomfort parameters.

Because of the aforementioned reasons the Department of Building Services and Process Engineering decided to investigate the effect of simultaneously present local discomfort parameters via human subject measurements.

In this paper a project is described in detail to show the methodological approach taken for the investigation of combined effects and to introduce results gained from experiments. The two local discomfort parameters studied were radiant temperature asymmetry and warm floor.

Experiments with human subject were conducted in a climate chamber, where one of the walls was cooled (to produce radiant asymmetry) and the floor was heated.

The hypothesis behind the investigation was as follows. Change (increase) in comfort is expected when the quality of an outside wall, or glass facade is increased so that its inside surface temperature is changed from 16°C to 18°C. For both cases the mean of heating is floor heating and its temperature is maintained at 28°C. Warm feet discomfort is expected due to the high temperature of the floor. It is hypothesized that the sensation of warm feet is lower in the presence of the 16°C wall.

As it can be seen, an important goal in indoor environmental research is the enhanced understanding of the mechanisms responsible for human perception to different exposures. Normally, human subjects are used for tests concerning perception of the environment, while experiments with manikins, equipped to resemble humans, may provide valuable information regarding velocities, temperatures near the human body.

A special case of comfort studies in the indoor environment is shown in the paper as well, namely the extensive air exchange in the room where a gas appliance with open combustion chamber is installed. The cold outdoor air entering through the air inlets may cause discomfort in the occupied zone, thus a model was worked out for the investigation of this case.

First a physical-mathematical model was developed that could be used for examining the non-steady-state condition of the room and the operation of gas boilers, chimneys and the air supply of the room together [9].

For the modelling of changes caused by the changes in the inside or outside ambient conditions, numerical investigation was used. The method of investigation was CFD (Computational Fluid Dynamics). The summary of the theoretical basis of numerical modelling was summarized in [10]. CFD can be used to obtain detailed information about the flow field and distribution of temperature inside a room. The results of the calculations can help in defining designing approaches and the requirements for different conditions.

3 Facilities and methods

3.1 Climate Chamber

The climate chamber, used for the experiment, is located within a room, thus it is unaffected by outdoor conditions. The chamber has the following dimensions: 3.8 m (L) x 3.1 m (W) x 2.5 m (H). The volume of the space equals to 29.5 m^3. Fig. 1. shows the layout and side view of the chamber. The chamber does not have windows, only artificial lighting is available.

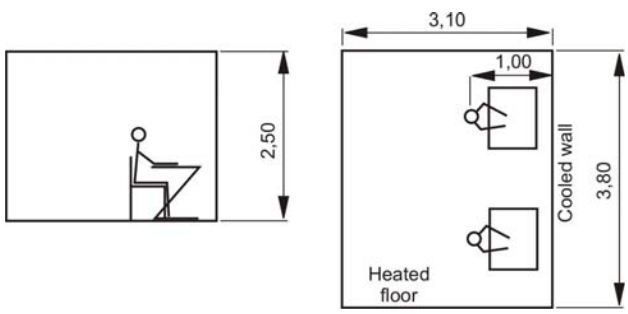

Fig. 1. Layout and side view of the chamber

The chamber's walls and floor are equipped with embedded surface heating or cooling systems. The surfaces can be cooled or heated by circulating water in any desired combinations. The water temperatures are controlled through a computer program, commonly used for building operation, in order to provide the required surface temperatures. In the current experiment, one of the walls (wall C) was cooled and the floor was heated simultaneously.

The chamber's air is served by an air handling unit, which heats and supplies outdoor air. The temperature can be controlled by a thermostat. The supply air enters the chamber through the perforated ceiling panels on the ceiling, resulting in very low air velocity (0.1 m/s), and it is removed through the grills on the sidewalls. During the experiment the unit was set to provide the minimum required fresh air for two persons.

Two desks and chairs were placed in the chamber; distances from the surfaces are also indicated in Fig. 1.

3.2 Physical measurements

The chamber is equipped with temperature sensors; Fe-CO thermocouples. Twelve sensors are distributed evenly and fixed on wall C, the cooled surface, and sixteen are mounted on the heated floor. The surface temperatures of the other walls are measured as well by 4 (wall D), 3 (wall A) and 3 (wall B) sensors. Air temperature is measured at heights 0.1 m, 0.6 m, 1 m and 1.7 m at two points respectively. All measured data is collected in a data logger in 1 minute intervals.

3.3 Experimental plan

The experimental plan for the investigation carried out during the spring of 2008 with two groups of subjects is seen in Table 1.

Table 1. Experimental plan

Week	Dates	Group No. (2prs/day)	Conditions wall / floor
1	31/04 – 04/04	1	16°C /28°C
2	07/04 – 11/04	2	18°C /28°C
3	14/04 – 18/04	1	18°C /28°C
4	21/04 – 25/04	2	16°C /28°C

The conditions followed a balanced order of presentation. Subject attended their two sessions on the same day of the week with two weeks difference (E.g. the 2 subjects coming on 31st of March, attended their second session on 14th of April).

The surface temperature of the wall varied between 16°C and 18°C, whereas the floor temperature was maintained at 28°C for all the session.

Other physical quantity controlled was the temperature of air, at 23°C.

3.4 Subjects

All together 20 subjects (10 males and 10 females) were recruited for the investigation. They were college age subjects between 20 and 28. Participants were divided into two groups. Two subjects were exposed per session. Sessions that were held always in the mornings lasted for three hours.

The 20 subjects selected were healthy, not suffering from any illnesses that would affect their thermal sensation according to the background questionnaire they completed before the experiment.

Subjects participating in the investigation were completely blind to the parameters investigated; no information or clues were given at any time.

Subjects were asked to wear t-shirts and trousers throughout the experiment (approx. 0.7 clo). They received a pair of socks and slippers after arrival. They were allowed to modify their clothing as desired, however were asked to indicate the time and action on a paper.

3.5 Subjective assessments

Upon arriving to the session, in the ante-room, subjects were asked when and what they had for a meal, whether they drank coffee, whether they smoked, if they had a good nights rest or not and if anything stressful occurred before coming. They also had to complete a questionnaire about their general state (ability to concentrate, freshness, tiredness).

Three times during each session, after entering the chamber, 1.5 h, and 3h of exposure, subjects were asked to complete a questionnaire, marking visual analog scales (VAS) to indicate their assessment of thermal comfort.

The VAS that were used in the investigation and the summery of the questionnaires are shown on Figure 2 and Table 2.

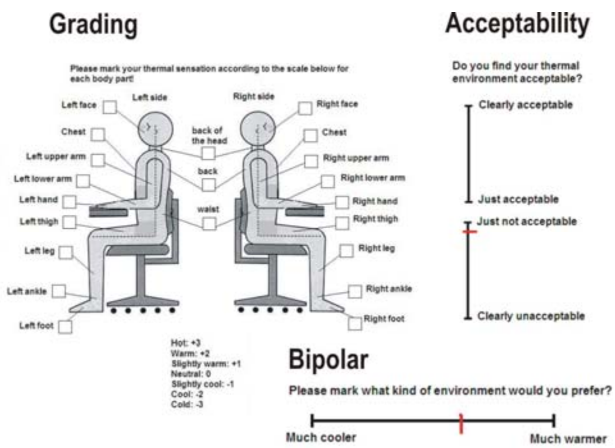

Fig. 2. Examples for the applied scales

Table 2. Summary of questionnaires and VAS

Variable	Type of scale	Low value	High value
General state			
Mental state	Bipolar	Interested	Bored
Mental tension	Bipolar	Relaxed, content	Upright, frustrated
Fatigue	Bipolar	Rested	Tired
Concentration	Bipolar	Easy to concentrate	Hard to Concentrate
Thermal comfort			
Thermal sensation	Thermal	Cold	Hot
Thermal evaluation	Bipolar	Comfortable	Uncomfortable
Thermal preference	Bipolar	Much cooler	Much warmer
Thermal environment	Accept-ability	Clearly Acceptable	Clearly unacceptable
Local sensation	Thermal - discrete	Cold	Hot

3.6 Objective physiological measurements

Three times, 0.1 h, 1.5 h and 3 h of exposure the skin temperature and the blood pressure of the subjects were measured.

The experimenter entered the chamber and with the help of a surface thermometer the following points were measured: forehead, nose, faces, ears, upper arms, lower arms, hands, chest, lower legs, ankles, feet and the back of the head. After this the blood pressures of the subjects were measured.

3.7 Experimental procedure

The three hour long sessions were run according to the schedule shown in Table 3. Subjects were seated on office chairs by two desks. They carried out simulated office work, proof reading and two-digit addition, to restrict them to remain close to their "workstations". Subjects could only leave the chamber if needed to go to the toilet. When not working they were allowed to read, study or talk.

Table 3. Schedule for the simulated office work

Clock time	Relative time	Event
08:45	-15 min	Arrival, general state and fatigue questionnaire
09:00	0 min	Enter chamber, thermal comfort questionnaire 1
09:10	10 min	Measure skin temperature and blood pressure
09:20	20 min	Start own activity
09:35	35 min	Start proof reading
10:10	70 min	Start addition
10:20	80 min	Thermal comfort questionnaire 2
10:30	90 min	Measure skin temperature and blood pressure
10:40	100 min	Start own activity
10:55	115 min	Start proof reading
11:30	150 min	Start addition
11:40	160 min	Thermal comfort questionnaire 3, general state and fatigue questionnaire
11:50	170 min	Measure skin temperature and blood pressure
12:00	180 min =3 h	Finish

3.8 Data processing and statistical analysis

The physical measurements were recorded automatically for subsequent computer analysis. The subjective votes marked on the VAS in the questionnaires were transcribed manually so that they could be further analyzed. Subjective assessments, except for the local sensation votes, and physical data were assumed to be normally distributed and they were analyzed by paired sample t-tests. Within sessions, repeated measures were used for variance. For the analysis of local sensation votes the non-parametric, marginal homogeneity test was used. For significance p-value was <0.05 indicating the tendency for the variable to differ between the conditions and sessions. Pearson-Bivariate correlation was applied to see whether subjective votes correlated with the measured skin temperature values.

4 Results from subjective assessments and from objective physiological measurements

4.1 General thermal comfort votes

The assessment of the 4 visual analogue scales in the questionnaires obtained after entering the chamber, 1.5h and 3h of exposure were analysed statistically using paired-sample t-test and repeated measures linear model.