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.

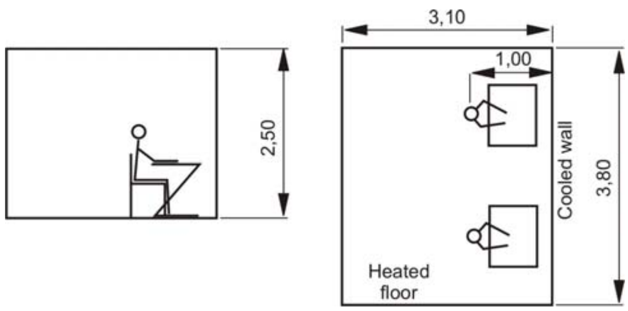

Fig. 1. Layout and side view of the chamber

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.

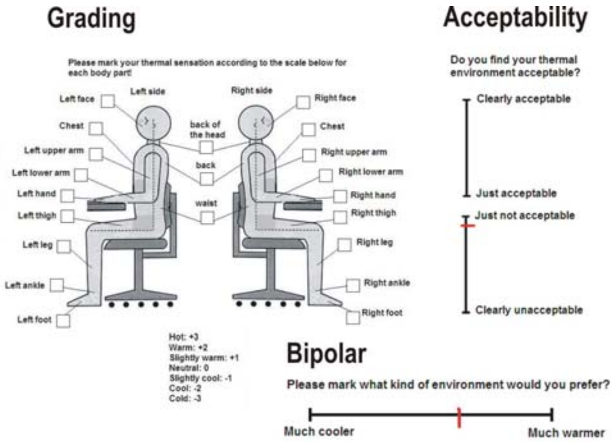

Fig. 2. Examples for the applied scales

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.

4.1.1 Thermal comfort votes between the two conditions

Table 4. shows results for the analysis of general thermal comfort votes between the two conditions.

Table 4. Statistical analysis of thermal comfort votes between conditions

Scales	Mean Cond.1/Cond.2	Paired-sample t-test
Thermal sensation: it is cold – it is hot		
1st.1 – 1st.2	-0.164 / 0.058	0.1198
2nd.1 – 2nd.2	-0.469 / -0.192	0.1664
3rd.1 – 3rd.2	-0.577 / -0.241	0.2733
Thermal evaluation: comfortable - uncomfortable		
1st.1 – 1st.2	33.430 / 34.781	0.7664
2nd.1 – 2nd.2	42.864 / 45.508	0.5223
3rd.1 – 3rd.2	51.732 / 41.255	0.0663
Thermal preference: prefer cooler – prefer warmer		
1st.1 – 1st.2	52.485 /51.562	0.6700
2nd.1 – 2nd.2	60.340 / 56.908	0.1854
3rd.1 – 3rd.2	62.505 / 57.149	0.1361
Thermal environment: acceptable - unacceptable		
1st.1 – 1st.2	0.527 / 0.610	0.2489
2nd.1 – 2nd.2	0.371 / 0.427	0.4968
3rd.1 – 3rd.2	0.307 / 0.500	**0.0397↓**

1st, 2nd, 3rd=number of the questionnaire within the session; 1, 2=number of condition (1=16°C wall. 2=18°C wall); bold numbers show values with significance ($p<0.05$), ↓= scale value/mean of the first condition is lower than second condition's.

No significant differences could be observed between the two conditions. The only exception is in the acceptability. Subjects found condition 2 significantly more acceptable at the end of the session than condition 1.

4.1.2 Thermal comfort votes within sessions

Table 5. shows results for the analysis of general thermal comfort within sessions, condition by condition. The t-test is carried out on before and after exposure votes.

Table 5. Statistical analysis of thermal comfort votes within sessions

Scales	Mean 1st vote/ 3rd vote	Paired-sample t-test
Thermal sensation: it is cold – it is hot		
1st.1 – 3rd.1	-0.164 / -0.577	0.1065
1st.2 – 3rd.2	0.058 / -0.241	0.1270
Thermal evaluation: comfortable - uncomfortable		
1st.1 – 3rd.1	33.430 / 51.732	**0.0006↓**
1st.2 – 3rd.2	34.781/ 41.255	0.2861
Thermal preference: prefer cooler – prefer warmer		
1st.1 – 3rd.1	52.485 /62.505	**0.0079↓**
1st.2 – 3rd.2	51.562/ 57.149	**0.0302↓**
Thermal environment: acceptable – unacceptable		
1st.1 – 3rd.1	0.527 / 0.307	**0.0029↓**
1st.2 – 3rd.2	0.610/ 0.500	0.2487

1st, 3rd=number of the questionnaire within the session; 1, 2=number of condition (1=16°C wall. 2=18°C wall); bold numbers show values with significance ($p<0.05$), ↓= scale value/mean of the first questionnaire is lower than third questionnaire.

Between the beginning and the end of sessions significant differences could be observed for condition 1 (16°C wall) regarding thermal evaluation, preference and acceptability votes. For condition 2 (18°C wall) only thermal preference showed significant difference. In all cases the scale values (means) increased by the end of the sessions, meaning that subjects felt more uncomfortable, preferred to have warmer environment and thought that environment is becoming more unacceptable.

4.1.3 Variance analysis of thermal comfort votes

Table 6. shows results for the analysis of general thermal comfort within sessions, condition by condition. The repeated measures variance test is carried out for the three questionnaires.

Table 6. Repeated measures analysis of general thermal comfort votes

Scales	Repeated measures
Thermal sensation: it is cold – it is hot	
1st.1 – 2nd.1	0.105
2nd.1 – 3rd.1	0.610
1st.2 – 2nd.2	0.246
2nd.2 – 3rd.2	0.798
Thermal evaluation: comfortable – uncomfortable	
1st.1 – 2nd.1	**0.037**
2nd.1 – 3rd.1	**0.047**
1st.2 – 2nd.2	**0.050**
2nd.2 – 3rd.2	0.278
Thermal preference: prefer cooler – prefer warmer	
1st.1 – 2nd.1	**0.026**
2nd.1 – 3rd.1	0.330
1st.2 – 2nd.2	0.101
2nd.2 – 3rd.2	0.929
Thermal environment: acceptable – unacceptable	
1st.1 – 2nd.1	**0.023**
2nd.1 – 3rd.1	0.277
1st.2 – 2nd.2	**0.035**
2nd.2 – 3rd.2	0.361

1st, 3rd=number of the questionnaire within the session; 1, 2=number of condition (1=16°C wall. 2=18°C wall); bold numbers show values with significance ($p<0.05$).

The repeated measures analysis shows that significant difference exist between the 1st and 2nd questionnaires except for thermal sensation. For condition 1 the significant change in evaluation, preference and acceptability was already preset by the 2nd questionnaire, i.e. after 90 minutes.

4.2 Local thermal comfort votes

The assessment of the grading scales in the questionnaires obtained after entering the chamber, 1.5h and 3h of exposure were analysed statistically using non-parametric marginal homogeneity test as discrete values (-3, -2, -1, 0, 1, 2, 3) were the inputs.

4.2.1 Local thermal comfort votes between the two conditions

Table 7. shows results for the analysis of local thermal comfort between the two conditions. The marginal homogeneity test is carried out for the conditions' first and third questionnaire votes.

Table 7. Statistical analysis of local votes between conditions

Body part	1st votes	3rd votes
Right face 1 – 2	0.3458	0.2482
Left face 1 – 2	0.5485	0.0736
Right upper arm 1 – 2	0.5316	**0.0133**
Left upper arm 1 – 2	0.7150	0.0906
Right lower arm 1 – 2	0.2568	**0.0152**
Left lower arm 1 – 2	0.3304	**0.0098**
Right hand 1 – 2	1.0000	0.2393
Left hand 1 – 2	0.8185	0.2170
Chest 1 – 2	**0.0348**	0.1967
Right lower leg 1 – 2	**0.0343**	0.2207
Left lower leg 1 – 2	0.5316	0.2393
Right ankle 1 – 2	0.1573	**0.0020**
Left ankle 1 – 2	0.1266	**0.0133**
Right foot 1 – 2	**0.0290**	**0.0056**
Left foot 1 – 2	**0.0422**	**0.0290**

1st, 3rd=number of the questionnaire within the session; 1, 2=number of condition (1=16°C wall. 2=18°C wall); bold numbers show values with significance ($p<0.05$).

Interestingly enough significance could be seen between the two conditions even at the beginning of the sessions. Significance could be found for several body parts (upper and lower arms, ankles and feet) for the 3rd votes between the two conditions.

Several body parts (back, back of the head, waist) were omitted from the analysis do to missing values.

4.2.2 Local thermal comfort votes within sessions

Table 8. shows results for the analysis of local thermal comfort within the sessions, condition by condition. The marginal homogeneity test is carried out for first and third questionnaire votes.

Table 8. Statistical analysis of local votes within sessions

Body part	Condition 1	Condition 2
Right face 1st – 3rd	0.3458	0.3711
Left face 1st – 3rd	**0.0330**	0.3173
Right upper arm 1st – 3rd	**0.0269**	0.2568
Left upper arm 1st – 3rd	**0.0431**	0.4652
Right lower arm 1st – 3rd	**0.0116**	1.0000
Left lower arm 1st – 3rd	**0.0241**	0.2367
Right hand 1st – 3rd	**0.0088**	**0.0269**
Left hand 1st – 3rd	**0.0105**	**0.0152**
Chest 1st – 3rd	0.0707	**0.0201**
Right lower leg 1st – 3rd	**0.0184**	0.0707
Left lower leg 1st – 3rd	**0.0495**	0.2393
Right ankle 1st – 3rd	**0.0027**	**0.0455**
Left ankle 1st – 3rd	**0.0094**	**0.0495**
Right foot 1st – 3rd	0.0589	**0.0061**
Left foot 1st – 3rd	**0.0496**	**0.0112**

1st, 3rd=number of the questionnaire within the session; 1, 2=number of condition (1=16°C wall. 2=18°C wall); bold numbers show values with significance ($p<0.05$).

During condition 1 the local thermal sensation for almost all body parts were significantly changed between the beginning and end of the session. From the mean values of votes (see Table 9.) it can be seen that by the end of the session subjects thermal sensation decreased to fall between -1(slightly cool) and -2 (cool). For condition 2 less body part votes (hands, ankles, feet) showed significant differences.

Table 9. Mean values of local thermal sensation votes

Body parts	Condition 1	Condition 2
Right face 1st	0.30	0.5
Right face 3rd	0.10	0.30
Left face 1st	0.40	0.55
Left face 3rd	-0.10	0.30
Right upper arm 1st	0.10	0.25
Right upper arm 3rd	-0.75	-0.05
Left upper arm 1st	0.15	0.25
Left upper arm 3rd	-0.60	0.05
Right lower arm 1st	0	-0,30

Body parts	Condition 1	Condition 2
Right lower arm 3rd	-1.15	-0.30
Left lower arm 1st	-0.20	-0.50
Left lower arm 3rd	-1.15	-0.15
Right hand 1st	-0.05	-0.05
Right hand 3rd	-1.20	-0.90
Left hand 1st	0	0.05
Left hand 3rd	-1.20	-0.80
Chest 1st	0.40	0.75
Chest 3rd	0.05	0.30
Right lower leg 1st	0.05	0.20
Right lower leg 3rd	-0.45	-0.15
Left lower leg 1st	0.05	0.20
Left lower leg 3rd	-0.40	-0.10
Right ankle 1st	-0.20	0.20
Right ankle 3rd	-1.10	-0.20
Left ankle 1st	-0.20	0.15
Left ankle 3rd	-1.00	-0.30
Right foot 1st	-0.65	0.25
Right foot 3rd	-1.50	-0.55
Left foot 1st	-0.60	0.20
Left foot 3rd	-1.45	-0.55

1st, 3rd=number of the questionnaire within the session; 1, 2=number of condition (1=16°C wall. 2=18°C wall).

4.3 Measured local skin temperatures

The measured local skin temperatures after entering the chamber, 1.5h and 3h of exposure were analysed statistically using paired-sample t-test and repeated measures linear model.

4.3.1 Locally measured skin temperatures between the two conditions

Table 10. shows the results of statistical analysis for skin temperature measurements between conditions.

Table 10. Statistical analysis of skin temperatures between conditions

Body parts	1st meas.	3rd meas.
Forehead 1 – 2	0.9395	0.1207
Nose 1 – 2	0.7738	0.1164
Right face 1 – 2	0.2246	0.1502
Left face 1 – 2	0.1833	0.0534
Right ear 1 – 2	0.2318	**0.0025↓**
Left ear 1 - 2	0.4111	**0.0420↓**
Right upper arm 1 – 2	0.7459	**0.0221↓**
Left upper arm 1 – 2	0.8452	**0.0068↓**
Right lower arm 1 – 2	0.1139	**0.0006↓**
Left lower arm 1 – 2	0.0788	**0.0000↓**
Right hand 1 – 2	0.7846	**0.0341↓**
Left hand 1 – 2	0.6660	**0.0191↓**
Chest 1 – 2	0.8335	0.2032
Right lower leg 1 – 2	0.3029	**0.0079↓**
Left lower leg 1 – 2	0.4059	**0.0067↓**
Right ankle 1 – 2	0.6792	**0.0159↓**
Left ankle 1 – 2	0.8414	**0.0052↓**
Right foot 1 – 2	0.2779	**0.0477↓**
Left foot 1 – 2	0.1253	0.0719
Back of the head 1 – 2	0.1295	**0.0118↓**

1st, 3rd=number of the measurement within the session; 1, 2=number of condition (1=16°C wall. 2=18°C wall); bold numbers show values with significance ($p<0.05$), ↓= mean value of the first condition is lower than second condition's.

No statistically significant difference could be found between conditions when the first skin temperature measurements were took. Comparing the third skin temperature measurements of the sessions for the two conditions almost all body parts showed significant changes. In all cases measured skin temperatures were lower in the case of condition 1.

4.3.2 Locally measured skin temperatures within sessions

Table 11. collects the results of statistical analysis for skin temperature measurements within sessions, i.e. between the beginning and end of the sessions.

Table 11. Statistical analysis of skin temperatures within sessions

Body parts	Condition 1	Condition 2
Forehead 1st – 3rd	0.6692	0.1037
Nose 1st – 3rd	**0.0009↑**	**0.0011↑**
Right face 1st – 3rd	**0.0001↓**	**0.0082↓**
Left face 1st – 3rd	**0.0000↓**	**0.0015↓**
Right ear 1st – 3rd	**0.0000↓**	**0.0004↓**
Left ear 1st – 3rd	**0.0000↓**	**0.0000↓**
Right upper arm 1st – 3rd	0.2105	0.2601
Left upper arm 1st – 3rd	0.1342	0.3311
Right lower arm 1st – 3rd	0.5767	0.2526
Left lower arm 1st – 3rd	0.1149	0.6133
Right hand 1st – 3rd	0.0727	0.5764
Left hand 1st – 3rd	0.0821	0.2537
Chest 1st – 3rd	**0.0028↓**	**0.0066↓**
Right lower leg 1st – 3rd	**0.0001↑**	**0.0019↑**
Left lower leg 1st – 3rd	**0.0000↑**	**0.0001↑**
Right ankle 1st – 3rd	**0.0000↑**	**0.0000↑**
Left ankle 1st – 3rd	**0.0000↑**	**0.0000↑**
Right foot 1st – 3rd	**0.0000↑**	**0.0000↑**
Left foot 1st – 3rd	**0.0000↑**	**0.0000↑**
Back of the head 1 – 2	**0.0001↓**	**0.0004↓**

1st, 3rd=number of the measurement within the session; 1, 2=number of condition (1=16°C wall. 2=18°C wall); bold numbers show values with significance ($p<0.05$), ↓= mean value of the first measurement is lower than third measurement's; ↑=mean value of the first measurement is higher than the third measurement's.

Within sessions significant changes could be found for the head and lower leg region of the body. For the case of ankles and feet very strong significance is indicated. No changes could be observed for the arms and hands within sessions for either condition.

Table 12. indicates the mean values of skin temperatures measured at the beginning and at the end of the sessions.

Table12. Mean values of skin temperatures

Body parts	Condition 1	Condition 2
Forehead 1st	34.23	34.24
Forehead 3rd	34.30	34.49
Nose 1st	31.84	32.05
Nose 3rd	28.49	29.18
Right face 1st	31.80	32.16
Right face 3rd	32.98	33.26
Left face 1st	31.99	32.38
Left face 3rd	33.29	33.59
Right ear 1st	29.73	30.10
Right ear 3rd	31.00	31.57
Left ear 1st	29.91	30.18
Left ear 3rd	31.33	31.79
Right upper arm 1st	31.73	31.66
Right upper arm 3rd	31.36	31.92
Left upper arm 1st	31.59	31.54
Left upper arm 3rd	31.23	31.84
Right lower arm 1st	32.19	32.56
Right lower arm 3rd	32.01	32.82
Left lower arm 1st	32.06	32.50
Left lower arm 3rd	31.63	32.61
Right hand 1st	31.17	31.04
Right hand 3rd	29.99	30.79
Left hand 1st	30.87	31.11
Left hand 3rd	29.52	30.55
Chest 1st	33.99	34.06
Chest 3rd	34.58	34.81
Right lower leg 1st	32.54	32.82
Right lower leg 3rd	31.55	32.07
Left lower leg 1st	32.54	32.74
Left lower leg 3rd	31.45	31.93
Right ankle 1st	31.13	31.25
Right ankle 3rd	29.00	29.75
Left ankle 1st	31.19	31.26
Left ankle 3rd	28.85	29.78
Right foot 1st	29.26	29.94
Right foot 3rd	26.30	27.63
Left foot 1st	29.18	30.18
Left foot 3rd	26.21	27.38
Body parts	Condition 1	Condition 2
Back of the head 1st	34.30	34.70
Back of the head 3rd	35.07	35.45

5 Discussion

Hypothesis: 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.

5.1 Subjective assessments

During the experiment subjects filled out questionnaires with VAS (see Fig. 2) about their general thermal comfort and local thermal sensation three times.

From the votes for general thermal comfort the following can be observed: no significant differences could be found between the two conditions, which probably means that general thermal comfort is unaffected by the increase in wall temperature – contrary to the basic hypothesis. The only exception is in the acceptability. Subjects found condition 2 significantly more acceptable at the end of the session than condition 1. It has to be noted that subject did not find these conditions unacceptable; the mean values were not negative.

Within sessions more significant differences were found. Compared to the 1st votes, in both conditions values increased or turned towards the less favourable part of the scales by the 3rd votes, however not always reached the level of significance.

As for condition 1, subjects felt more uncomfortable, would have preferred a warmer environment and found the thermal environment more unacceptable by the end of the session. For condition 2 the only significant value was about thermal preference; i.e. subjects would have preferred a warmer environment, but still found the actual environment acceptable and comfortable.

Variance analysis pointed out that where significance was found between the votes it occurred mostly by the second questionnaire. This could mean that changes in general thermal comfort already happen by the middle of the session, by the 90th minute.

From the results of local thermal comfort votes the following can be observed: When comparing conditions, votes for some body parts already showed significance differences at the beginning of the sessions. From the mean values given in Table 9. it can be seen that in the case of condition 2 higher votes (closer to neutral) were given compared to condition 1. This could be explained by the effect of floor heating. It has to be noted that the discomfort parameter of warm feet is not indicated in the sensation votes. On the contrary, it seems that subjects have not noticed or could not feel the high floor temperature. They voted that their ankles and feet feel cooler by the end of sessions. This is opposite to the hypothesis.

Within sessions, condition 1 (16°C wall) gave significant results for almost all body parts. From the mean values it can be seen that subjects voted between -1 (slightly cool) and -2 (cool) for the leg region and arms, hands. Compared to this in condition 2 smaller drops can be seen between the first and third votes (0 to -1; between neutral and slightly cool), meaning that subjects were less affected by the wall and more affected by the floor.

5.1 Objective measurements – skin temperature

Significant differences could be only found between the 3rd measurements of the two conditions. For the 3rd measurement the temperature of all body parts was lower in the case when the 16°C wall was present. This supports the hypothesis that increasing the quality of the wall will cause less cooling/discomfort in the body parts.

It has to be noted that not only the sensation votes, but the measured temperatures reveal that floor heating does not cause warm feet, but only able to help to reach a close to neutral state from the lower side.

This is more strongly shown when the 1st and 3rd measurements are compared within sessions. The very strong significance for the lower leg region between the first and third measurement suggests that for both conditions, independently on the wall temperatures, the temperature of these body parts will decrease during the session. The decrease however will be less in the case of 18°C wall.

It can be stated that the skin temperature of the body parts decreases within sessions, however in the case of 18°C it decreases less.

Another factor has to be included when examining skin temperatures and it is the sitting posture of the occupants. The lack of movement adds to the decrease of skin temperature.

6 Modelling of comfort issues – air distribution in rooms

CFD method was used for the investigation of extensive air exchange in the room where a gas appliance with open combustion chamber is installed.

For the modelling of the B11 type gas appliance a conventionally sized room is used, in which the appliance is the only equipment (Fig.3). The volume of the room is 15 m3, and its size in detail is: 2 m (width), 2.5 m (length), 3 m (height). The windows and doors of the room are air-tight structures made of wood or plastic, sealed with several layers of rubber sealing.

Outside air can barely or cannot enter at all in the room through natural (gravitational) means. The air necessary for combustion is provided via air inlets that in the model were inserted in the window frame in different ways, under and above the window.

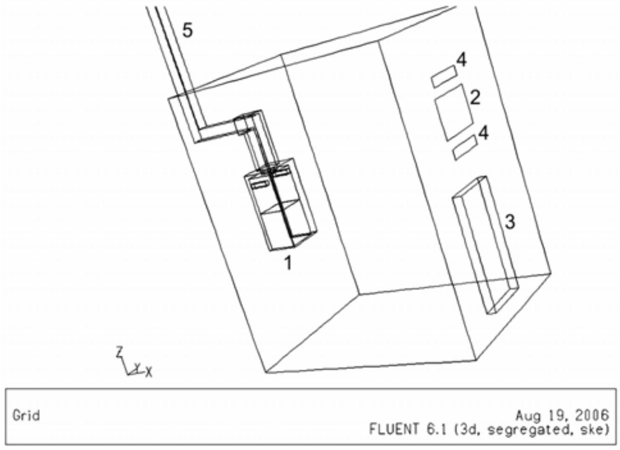

Fig.3. The geometric model used for the examination of B11 type gas appliances

1 – wall-mounted gas appliances, 2 – window, 3 – radiator, 4 – air inlet, 5 – chimney

The U-value of the external wall is 0.45 W/m2•K, while the window has a U-value of 1.4 W/m2•K.

Under the window a radiator is situated that is controlled by a thermostatic radiator valve which adjusts the heat loss so that the desired room temperature is achieved.

Nominal heat output of the gas appliances in the investigation are: 12 kW, 24 kW, 28 kW and 36 kW.

The connecting flue pipe consists of: 0.5 m long vertical section, bend, 1 m long horizontal section. The pipe is made of aluminium and has a maximum absolute roughness of 1 mm.

The chimney is situated partly in the heated space and partly outside.

The outdoor air temperature is -15 °C, which is the best condition regarding the chimney but is the worst from the room's comfort point of view.

The phenomenon was studied with the help of CFD, in a virtual computational environment. CFD modelling gives results for the changes in the magnitude and direction of air velocity in the room and between the air inlet and the appliance, temperature distribution in the room and from the weather factors, the effect of wind on the operation of the air inlet.

Steps of the CFD modelling:

– creating the geometry of the model,
– stating the differential equations for the numeric model,
– developing the CFD model,
– modelling the air supply for different conditions and operation modes, compute the air velocity and temperature distribution in the room.

The numeric model, based on the geometric model, was developed by adding principal initial and boundary conditions.

The air movements of closed areas are described by the differential equations of continuity and Navier-Stokes. The thermo balance of the areas is expressed by the equation of energy; its distribution of concentration is described by the differential equation of material balance. As we are talking about turbulent air conduction, also the proportion of the kinetic energy and the dissipation (k-ε) of the airflow has to be determined. Resulting from a system of equations, this is the mathematical model of closed spaces.

6.1 Results of the CFD investigation

Fig.4 and Fig.5 show the temperature and velocity distributions in the room ([11], [12]).

It can be seen on Fig.4 that the air coming through the air inlet is heated up quickly and the temperature in the occupied zone is between 20 and 22 °C. Fig.5 shows, that in the occupied zone velocities are far below 0.1 m/s.

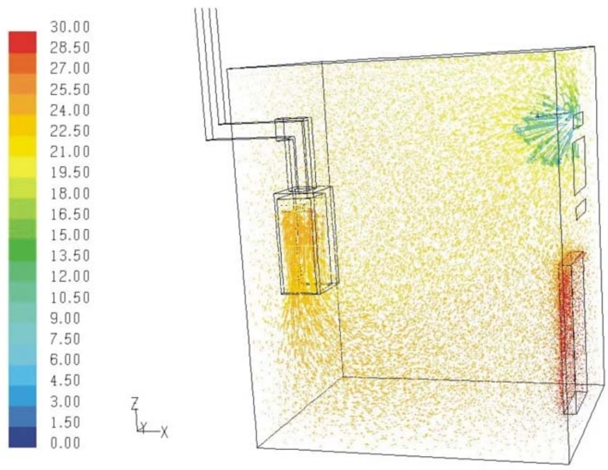

Fig.4. Temperature distribution in the room

From the distributions indicated in Fig.4 and Fig.5 the following can be stated:

– the average air temperature in the occupied zone is adequate (24 °C) and uniform,
– the relative air velocity in the occupied zone is far below 0.1 m/s,
– the air velocity in the occupied zone has a uniform distribution,
– 30 cm from the air-inlet the entering fresh air has a temperature that hardly differs from the average air temperature of the room,
– it is reasonable to place a heat-transfer appliance (accurately sized radiator) under the air-inlet so that the cool zone of the air-inlet can be reduced.

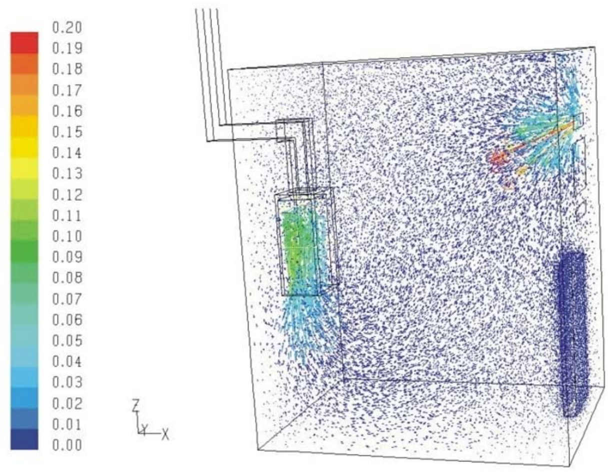

Fig.5. Velocity distribution in the room

Based on the results of CFD modelling, PMV values were also calculated for the room. Results show that in case of 0.8 clo, which is considered a light clothing ensemble, and for the activity level of 1 met, PMV values fall between -0.3…+0.1. This region stands for a slightly cool and comfortable thermal comfort level.

7 Conclusions

The paper outlines two methods, experimental measurements and CFD modelling, that can be applied to describe the comfort/discomfort conditions that may be present in our indoor environment.

Method1: Human subject experiments are of importance as they may be used to obtain relationships that later could be used for the verification of CFD simulations. The experiment described in the paper was carried out to observe how the thermal sensation of subjects change when the quality of a badly insulated wall or glass facade is increased and the floor temperature is high.

Results showed that general thermal comfort was unaffected by the increase of wall temperature. However, it was found that within a session general thermal comfort significantly decreased, especially for the condition when the wall temperature was 16°C. Votes for the local thermal sensation revealed that no discomfort due to warm feet can be expected for either conditions, i.e. floor heating helped probably to maintain a close to slightly cool or neutral sensation. Skin temperature measurements showed that the warmer condition resulted in higher skin temperatures compared to the cooler one. Matching the local sensation votes the temperature of the leg region decreased during the sessions for both conditions.

Method2: CFD modelling may be applied in the case of room air distribution simulations where extensive air exchange is present. By finding the correct position of air inlets with modelling the discomfort due to draughts and cold air can be avoided.

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